



# ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

## Refrigerated Warehouse Demand Response Strategy Guide

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## Preface

Refrigerated warehouses are ideal candidates for implementing demand response strategies due to a unique combination of factors:

- **High potential:** The energy used to run industrial-sized refrigeration systems is significant. Refrigeration loads account for approximately 16% of the food industry's total energy use (Goli et al.2011). Furthermore, their energy usage is often synchronized with the ambient temperature, such that usage peaks during the hottest hours of the day when demand response is the most valuable.
- **High tolerance to brief service interruptions:** Refrigerated warehouses are typically well insulated. The insulation, combined with the high thermal mass of the stored product within the warehouse, allows operators to reduce the cooling capacity for a few hours if needed without excessive space temperature changes, compromising stored product integrity, or materially disrupting facility operations.
- **Relatively simple implementation:** The processes in refrigerated warehouses are limited in number and are well understood by system operators. Many refrigerated warehouses are already equipped with control systems that are sufficiently sophisticated to integrate demand response controls. While there has been limited participation by the industry in demand response activities to date, industry experience is growing rapidly and there are numerous refrigerated warehouse facilities in the U.S. that have successfully integrated demand response strategies, including automatic demand response.

In a July 2012 report, “The Impact of Control Technology on the Demand Response Potential of California Industrial Refrigerated Facilities,” Scott et al. presented the landscape of control systems found in California’s industrial refrigerated facilities, including details about common control devices and architectures. The report also considered and presented the pitfalls and barriers to demand response related to facility type, refrigeration system characteristics, and control system shortfalls. It also identified how an integrated control design can be used to overcome these challenges.

This guide is intended to aid refrigerated warehouse facility operators, managers, and owners in determining whether it makes sense, and if so how, to implement energy efficiency measures and/or demand response control strategies that provide a reasonable payback for their particular operation. The aspects addressed by this guide include:

- Energy efficiency, load shedding, and load shifting strategies, and how they can be employed in various configurations of refrigerated warehouses, including the degree of control and automation required to properly implement them.



- Specific areas within a refrigerated warehouse that are best suited to use the above mentioned strategies, as well as the operational sustainability of such strategies.

## Organization and Content

This guide is organized into three main sections and three appendices:

### Section 1: Quick Start Guidance

**Introduction to Demand Response.** The concept of demand response is defined and explored, including why it is important not only to facility operators but also to grid operators, utility companies, and society in general. The section also covers how demand response works, the different types of demand response, and the relationship of demand response to other demand curtailment-related strategies such as permanent load shifting.

**Roadmap for Adopting DR Measures.** In this section, specific demand response strategies for refrigerated warehouses are explored.

### Section 2: Economics of Demand Response

**Economics of Efficiency and Demand Response.** In this section, the cost of implementing energy efficiency measures and demand response capabilities is explored.

**Quantifying Demand Response Potential.** This section correlates system capacity to demand response potential by summarizing operating data that were collected from several existing facilities.

**Case Studies.** Field studies were conducted at several different refrigerated warehouses in California, in which temperature measurements were taken before, during, and after simulated demand response events. Hourly simulations were also utilized for two locations to further investigate demand response elements and considerations that the field studies could not capture. A summary of the analyses and conclusions is presented in this section.

### Section 3: Identifying Facilities Suited to Demand Response

**Considerations for Demand Response.** This section presents the most important aspects of refrigerated warehouse operations that must be considered if demand response is to be implemented. The section also covers the minimum control system requirements for implementing demand response at a refrigerated warehouse facility, and concludes with a discussion about safety in relation to demand response.

**APPENDIX A: Introduction to Energy Efficiency.** Several of the most common energy efficiency measures for refrigerated warehouses are presented. This appendix also elaborates on the relationship between energy efficiency and demand response.

**APPENDIX B: Field Study Details.** In the field studies, factors such as air circulation, space geometry, construction vintage, infiltration air volume and management tactics, and evaporator fan speed were evaluated to determine which factors affect the ability to implement demand response. This appendix provides details about these studies.

**APPENDIX C: Energy Model Analysis Details.** Topics that are covered in this appendix include: the repercussions of permanent load shifting (PLS) and demand response on consecutive days, the effect of precooling (or over-cooling) before demand response events, and the effect of building and product mass on space temperature rise during demand response.

## ABSTRACT

This guide summarizes demand response measures that can be implemented in refrigerated warehouses. In an appendix, it also addresses related energy efficiency opportunities. Reducing overall grid demand during peak periods and energy consumption has benefits for facility operators, grid operators, utility companies, and society.

State wide demand response potential for the refrigerated warehouse sector in California is estimated to be over 22.1 Megawatts. Two categories of demand response strategies are described in this guide: load shifting and load shedding. Load shifting can be accomplished via pre-cooling, capacity limiting, and battery charger load management. Load shedding can be achieved by lighting reduction, demand defrost and defrost termination, infiltration reduction, and shutting down miscellaneous equipment. Estimation of the costs and benefits of demand response participation yields simple payback periods of 2-4 years.

To improve demand response performance, it's suggested to install air curtains and another form of infiltration barrier, such as a rollup door, for the passageways. Further modifications to increase efficiency of the refrigeration unit are also analyzed. A larger condenser can maintain the minimum saturated condensing temperature (SCT) for more hours of the day. Lowering the SCT reduces the compressor lift, which results in an overall increase in refrigeration system capacity and energy efficiency. Another way of saving energy in refrigerated warehouses is eliminating the use of under-floor resistance heaters. A more energy efficient alternative to resistance heaters is to utilize the heat that is being rejected from the condenser through a heat exchanger. These energy efficiency measures improve efficiency either by reducing the required electric energy input for the refrigeration system, by helping to curtail the refrigeration load on the system, or by reducing both the load and required energy input.

Keywords: Demand response, refrigerated warehouses, energy efficiency, cold storage, AutoDR, load shifting, load shedding, variable speed control

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## Executive Summary

This strategy guide is intended to assist refrigerated warehouse owners and operators in making strategic decisions related to implementing an electric demand management strategy at their facility, including demand response. Demand response is a set of strategies used to manage the demand-side load on the electric grid as a way to balance the supply and demand of electricity. Refrigerated warehouses present an opportunity to shift a significant amount of electric demand, but they also exhibit unique system, operational, and control challenges that must be addressed before a demand response strategy can be safely and effectively implemented.

In addition to demand response, several common energy efficiency measures and control strategies are described in this strategy guide. Energy efficiency for refrigerated warehouses should be considered in concurrence with demand response. Industrial refrigeration uses a significant amount of electricity on a year-round basis and operating refrigeration plants efficiently has become increasingly important. Many energy efficiency measures offer increased flexibility and a heightened level of control over the refrigeration system, creating opportunities to implement more advanced demand response approaches.

This guide expands on the complex relationship between energy efficiency and demand response. The work explores which energy efficiency measures increase operating flexibility (e.g. improved demand response), when coupled with smart controls; as well as which measures and methods serve a dual purpose (i.e. to the benefit of both energy efficiency and demand response). The work also points out where certain measures could work at cross purposes (i.e. with competing objectives to the detriment of demand response or energy efficiency or owner's cost), and how these competing objectives can be balanced through more integrative analysis, design, and control. Finally, the guide also distinguishes between demand response and permanent load-shift strategies, and weighs the benefits and challenges of both approaches.

The guide incorporates the findings from field studies that were conducted at several different refrigerated warehouses in California, in which air temperature and product surface temperature were measured before, during, and after simulated demand response events. The guide explores the role played by air temperature, product mass, building mass, and various construction features on the space temperature during steady-state operation, and the temperature rise during demand response events. The work also investigates which warehouse usage characteristics, maintenance circumstances, and design features combined to produce local areas of relatively warm air during steady-state operation, and/or contribute the most to space temperature rise during demand response events. Factors such as air circulation, space geometry, construction vintage, infiltration air volume and management tactics, and evaporator fan speed are considered.

# Section 1. Quick Start Guidance

## 1.1 Introduction to Demand Response

Here, the concept of demand response is explored, including why it is important to not only facility operators but also grid operators, utility companies, and society in general. The introduction also covers how demand response works, the different types of demand response, and the relationship of demand response to other demand curtailment-related strategies such as permanent load shifting.

### 1.1.1 Goal of the Guide

The guide is intended to assist refrigerated warehouse owners and operators in making strategic decisions related to implementing an electric demand management strategy at their facility, including DR. This guide expands on the complex relationship between EE and DR. The work explores which EE measures increase operating flexibility (e.g., improved DR), when coupled with smart controls; as well as which measures and methods serve a dual purpose (i.e., to the benefit of both EE and DR). The work also points out where certain measures could work at cross purposes (i.e., with competing objectives to the detriment of DR, EE, or owner's cost), and how these competing objectives can be balanced through more integrative analysis, design, and control. Finally, the guide also distinguishes between DR and permanent load-shift strategies, and weighs the benefits and challenges of both approaches.

### 1.1.2 What is Demand Response?

“Demand response” is a set of actions taken by electrical grid end-users, at the request of grid operators, to reduce, shift, or increase a facility's normal operating electric load, for the purpose of temporarily modulating the overall demand on the electric grid. It offers one way for grid operators to ensure that the demand for electricity does not exceed the available supply, which would result in power interruptions in the form of rolling brownouts or blackouts,<sup>1</sup> or to make use of excess power flowing to the grid during times of over-generation. Electric grid demand may out-pace supply for any combination of reasons, including:

- Constraints on generation capacity, such as when power plants are down for repair or maintenance, or when reserve generation capacity is not prepared to react to sudden changes in grid demand.<sup>2</sup>

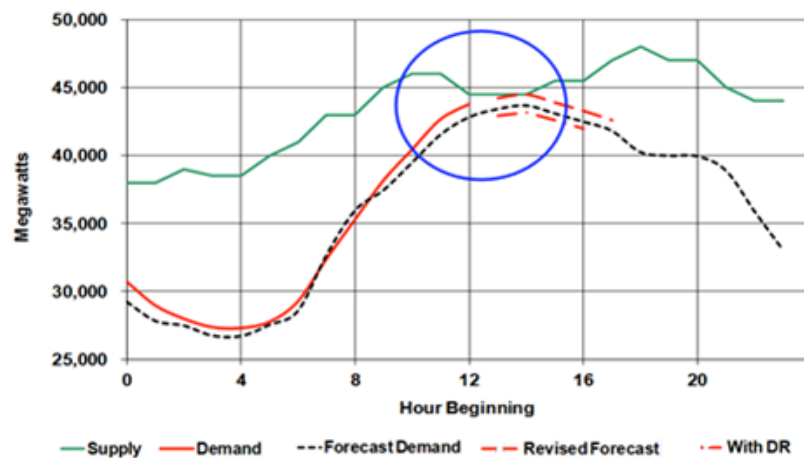
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<sup>1</sup> A brownout is an intentional or unintentional drop in voltage in an electrical power supply system. A blackout is a short- or long-term loss of electric power to an area.

<sup>2</sup> For example, a non-spinning reserve. Spinning reserve refers to a power plant that is on, but not contributing to the grid. It is stand-by capacity that can rapidly respond to peaks in demand. Non-

- Constraints on transmission capacity, or line outages.
- Extreme weather forecasts—hot weather places the most demand on utility grids whose peaks are cooling-driven, and cold weather places the most demand on grids whose peaks are heating-driven.
- Emergencies declared by grid operators, which may be called for any of the above reasons.

Demand response events are typically declared when the forecasted demand for energy is within 15% of the forecasted supply (Wylie 2013). As an example, Figure 1 shows electricity supply and demand from the California Independent System Operator (CAISO) for an actual demand response event for a day in 2012.

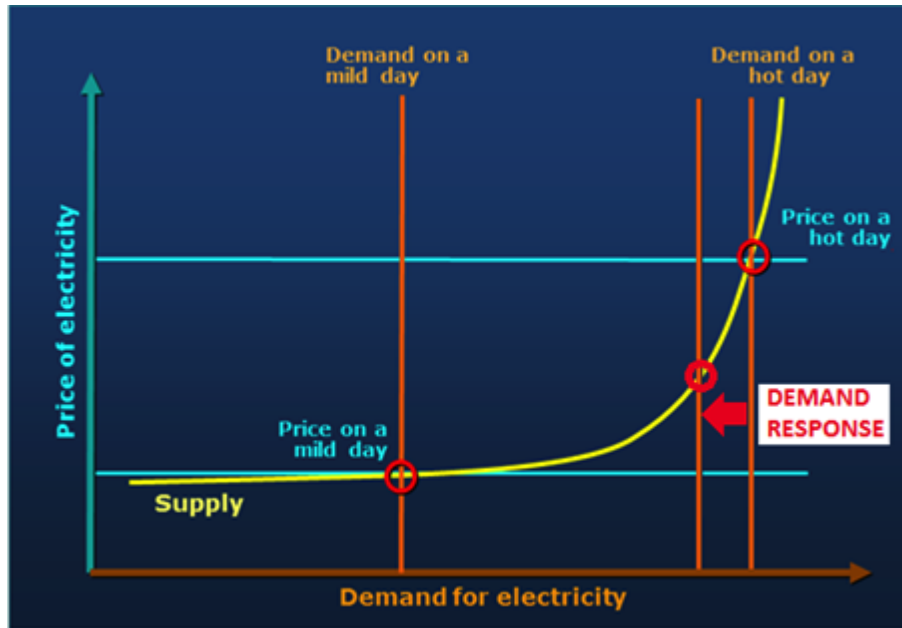


**Figure 1: Electricity supply and demand for an actual demand response event day in 2012.**

A demand response event may also be triggered by a forecast of high energy prices on the wholesale energy market. Energy prices, as with the price of most commodities, are subject to the principle of supply and demand. In virtually all power systems, electricity is produced by generators that are dispatched in order of increasing marginal cost, meaning that the plants with the lowest cost of production are used first, followed by the next cheapest, and so on, until the instantaneous electricity demand is satisfied. In this model, the wholesale price of electricity is equal to the marginal cost of the highest cost generator that is contributing energy into the grid, which will vary with the level of demand. Therefore, by reducing the demand for electricity, the price is also reduced, as shown in Figure 2.

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spinning reserve refers to a power plant that must be activated first, and is thus slower to respond to surges in demand



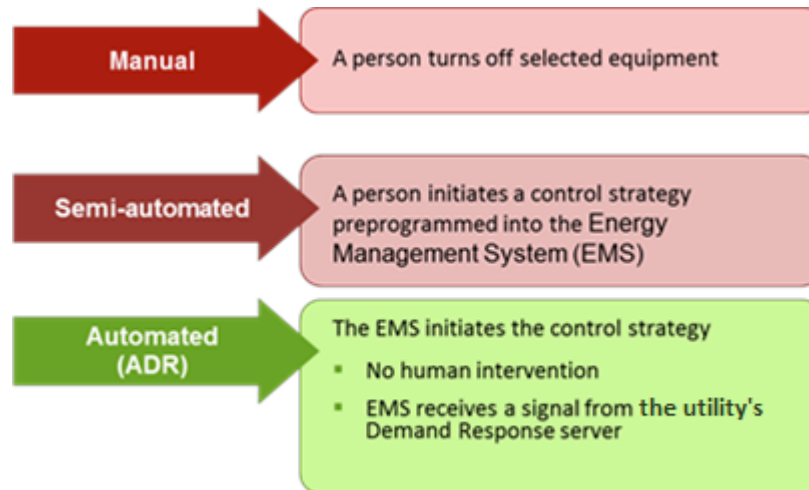
**Figure 2: Supply and demand relationship affecting the price of electricity.**

Demand response is a valuable tactic that benefits the facility operator, the utility company, and grid operators, as well as society in general. Demand response:

- Keeps electricity costs down by reducing the demand for electricity.
- Facilitates integration of renewable energy sources such as wind and solar power into the grid. Wind and solar energy supply can shift rapidly with rapid changes in weather, but the impact of these changes can be reduced (i.e., stabilized) with strategies like demand response.
- Defers, or completely avoids, the need to build and maintain additional power plants and transmission lines, at a considerable capital and environmental cost.

### 1.1.3 How Demand Response Works

The term “demand response” encompasses electric load-reduction strategies that are both manually initiated and automatically initiated. Figure 3 summarizes the three main approaches to demand response at an industrial facility.



**Figure 3: Manual, semi-automated, and automated demand response**

Automated demand response, also known as Auto-DR or ADR, is an automated system in which electric load from participating facilities is shed automatically. No direct human intervention is required by the facility operator to initiate the load shed. In Auto-DR programs, utilities and independent system operators (ISOs) directly manage peak energy consumption by broadcasting price and reliability signals to participating facilities. Smart controls at the facility receive these signals and communicate with the facility's building automation systems or process equipment, which automatically reduce energy use based on shed (signal) strategies that participants configure in advance. Facility personnel often have the ability to opt-out of events, but Auto-DR requires that participation occur by default.

Facilities that participate in demand response programs do so through their supplying electric utility. Participants are typically required to have a "smart meter" that can monitor energy usage at daily intervals and communicate usage in real-time to the utility. Energy and demand tariffs for participating facilities are normally based on a Time of Use (TOU) format, which tiers pricing according to on-peak, mid-peak and off-peak schedules. During demand response events, participating facilities pay an energy price that is an order of magnitude more expensive than typical peak-day prices.

Aggregators can also facilitate demand response. Aggregators are brokers that act on behalf of a group or groups of customers. They enlist end users to participate in demand response curtailment and sell the combined load reduction to utilities and grid operators, and consolidate demands from many small users to reach minimum participation levels. Aggregators can "spread the risk"—if one site in an aggregate portfolio cannot shed any load, others can be leaned on to make up the difference, as opposed to direct participation where penalties may be levied on individual customers for failing to hit contractual load-shed goals.

#### **1.1.4 Demand Response and the Refrigerated Warehouse**

Industrial refrigerated warehouses are excellent candidates for implementing demand response strategies. The refrigerated warehouse sector consumes a substantial portion of the total grid energy; in a study prepared by the U.S Department of Agriculture, there are 560 million cubic feet of gross refrigerated warehouse space in the state of California alone (United States Department of Agriculture, 2014). Assuming an average of 60 tons of refrigeration capacity per million cubic feet (Stoecker, 1998) and an average of 1.1 kW of electric power per ton of refrigeration capacity, this translates to approximately 37 MW of total refrigeration electric demand for the refrigerated warehouse inventory in California. In addition, refrigerated warehouses exhibit a unique combination of factors that are favorable for demand response:

- Refrigeration loads account for a significant portion of the facilities' total energy usage.
- Their usage is often greatest during utility peak periods.
- The thermal mass of the stored product in the insulated spaces can often tolerate reduced cooling capacity for a few hours when needed.

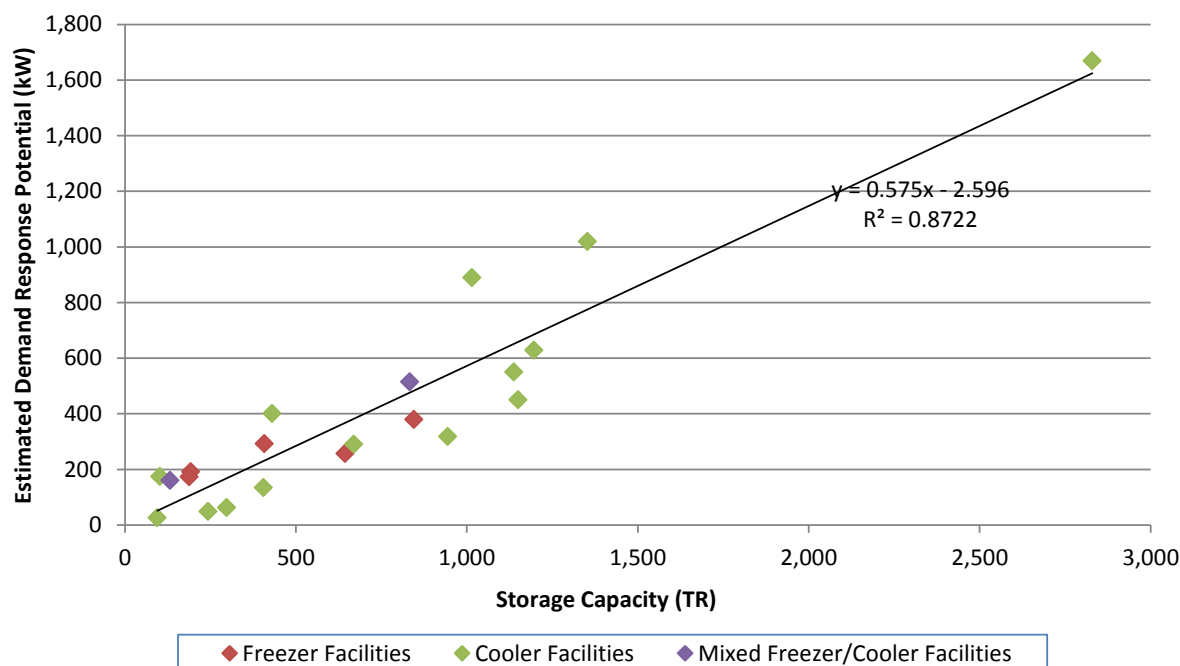
Performance monitoring software was used to estimate the demand response potential of twenty refrigerated warehouses in California (Table 1).

**Table 1: Demand response estimates of potential for 21 refrigerated warehouse facilities**

Facility	Total Capacity (TR)	Storage Capacity (TR)	Product Type	Size (S.F.)	County	Storage Temperature	Estimated DR Potential (kW)
<b>Freezer Facilities</b>							
1	845	845	Frozen Food	24,000	San Diego	+0°F	380
2	192	192	Frozen Food	50,000	Los Angeles	+10°F	192
3	188	188	Frozen Food	72,000	Los Angeles	+0°F	173
4	408	408	Frozen Food	132,000	Orange	-5°F	292
5	1,867	644	Frozen Bakery	84,000	Glynn (Georgia)	-15°F	257
<b>Cooler Facilities</b>							
6	2,944	95	Cheese	10,000	Kings	+5°F	26
7	562	102	Bakery Goods	40,000	Los Angeles	-10°F	174
8	515	405	Produce	25,000	Santa Cruz	+35°F	135
9	297	297	Beverage	60,000	Kern	+38°F/+60°F	63
10	1,022	243	Produce	65,000	Santa Cruz	+28°F	48
11	2,109	1,015	Produce	128,000	Monterey	+35°F	890
12	669	669	Bakery Goods	137,000	Los Angeles	+38°F	290
13	5,513	2,829	Produce	224,000	Kern	+38°F	1,669
14	2,874	1,353	Produce	250,000	Fresno	+32°F	1,020
15	2,959	1,196	Produce	268,000	Monterey	+32°F	629
16	1,411	945	Produce/Deli	306,000	Los Angeles	+35°F	318
17	1,138	1,138	Produce/Deli	355,000	Los Angeles	+32°F	550
19	2,337	1,150	Produce	115,000	San Benito	+35°F	450
<b>Mixed Freezer/Cooler Facilities</b>							
20	833	833	Misc.	207,000	Alameda	+0°F/+28°F/+38°F	515
21	132	132	Seafood	38,000	Los Angeles	+10°F/-10°F	161

The estimate of potential is equal to the demand of the refrigeration system serving long-term storage. While some facilities are dedicated refrigerated warehouses providing public storage spaces for different customers, most facilities have refrigeration needs for both processing and long-term storage. Only considering demand shed of refrigeration power used for long-term storage provides a conservative and realistic estimate of demand response potential. The estimated demand response potential versus long-term design storage capacity from Table 1 is presented in Figure 4.





**Figure 4: Estimated demand response potential versus storage capacity**

The correlation depicted in Figure 4 can be used to forecast the demand response potential of the population of refrigerated warehouses in California. Using the gross cubic footage of refrigerated warehouses in California from the U.S. Department of Agriculture’s Economics, Statistics, and Market Information System, and assuming an average refrigerated warehouse capacity of 60 tons of design refrigeration capacity per million cubic feet (Stoecker, 1998) and typical safety factors, the state-wide demand response potential for the refrigerated warehouse sector can be estimated as over 22 Megawatts.

Shifting demand in a refrigerated warehouse presents unique challenges, however, related primarily to guaranteeing that 100% of the stored product remains at acceptable temperatures, even though the refrigeration system is shut off (or the capacity has been significantly curtailed) during a period of the day that usually coincides with the hottest hours of the year as well as the peak work hours of the day. In addition, refrigerated warehouse systems must be sufficiently robust, and refrigeration controls sufficiently automated, to facilitate safe shutdown and startup of the system without diverting excess worker attention and other resources during a demand response event.

### 1.1.5 Demand Response and Permanent Load Shifting

Permanent Load Shifting, or PLS, which refers to permanently shifting refrigeration load from peak periods to off-peak, is an option for facilities with flexible production schedules or minimal quick cooling needs. Many of the successful criteria to implement PLS are the same as demand response.

A central issue with permanent load shifting is the trade-off between the economic benefit of a reduction in peak demand and the incremental cost of making up for the corresponding load in a shorter amount of time. This incremental cost is incurred because the daily heat load needs to be removed from the space in fewer hours, with inherently lower efficiency due to higher fan speeds and higher heat exchanger approaches. Additionally, the cooling system must have a higher capacity in order to handle the higher heat load in these hours.

In Appendix A, the importance of energy efficiency is explored for refrigerated warehouses, and the relationship between demand response and energy efficiency is also explored.

## 1.2 Roadmap for Adopting DR Measures

Table 2 lists eight demand response strategies for refrigerated warehouses.

**Table 2: Demand response strategies overview**

Strategy	Description
<b>Load Shifting Strategies</b>	
Precooling	Shift a portion of the peak-day refrigeration load to the off-peak hours <i>ahead</i> of a DR or load-shift event.
Capacity Limiting	Limiting the capacity (and power) of refrigeration equipment, rather than turning it off outright during DR. For refrigeration systems, capacity limiting should occur at the evaporator coils, either through limiting fan speed (or duty cycle for fan-cycling systems), or through turning off select units.
Battery Charger Load Management	Forklift and pallet lift battery chargers can be shut off during DR events. There must be an adequate number of battery chargers and battery packs available to pre-charge a reserve quantity of battery packs for use during DR.
<b>Load Shedding Strategies</b>	
Lighting Reduction	Shut off select lights during DR. Quick-starting fixtures such as T8 and T5 fluorescents and LED fixtures can be used in conjunction with control devices such as occupancy sensors
Demand Defrost and Defrost Termination	Defrost load can be shed through the use of technologies that initiate defrost cycles based on the level of frost buildup on the coil (e.g. demand defrost). These technologies avoid most of the excessive heat that is introduced into a space from scheduled, time-terminated coil defrosts.
Infiltration Reduction	Reduce air infiltration into refrigerated spaces from outside or from higher-temperature spaces during demand response.
Turning Off Miscellaneous Equipment	Unique, site-specific opportunities to shed electric load by simply turning off equipment that is not in use during peak hours.
Increasing Space Temperature Set Point	Effectively similar to shutting down the refrigeration system — refrigeration compressors simply turn off (or reduce capacity if serving other refrigeration loads) until the space temperature rises to the new higher set point.

In general, demand response strategies can be categorized as load *shifting* strategies, which move the load from one operational period to another, and load *shedding* strategies, which avoid the load altogether.

### **1.2.1 Load Shifting Strategies**

Load shifting is a process of redistributing energy use for refrigeration from on-peak or event hours when demand and rates are highest to off-peak hours when rates are lower, by utilizing the thermal capacitance of the stored product. The three load-shifting methodologies described in this section are:

- 1) Precooling
- 2) Limiting Refrigeration System Capacity
- 3) Battery Charger Load Management

#### ***1.2.1.1 Precooling***

Precooling, or over-cooling a refrigerated space, shifts a portion of the peak-day refrigeration load to the off-peak hours ahead of a demand response or load-shift event. Energy modeling of an example warehouse (presented later in the next section) showed that precooling is an effective way to curtail the space temperature rise during a demand response event when refrigeration is off. However, the energy model also indicated that precooling increased the overall refrigeration system energy usage by approximately 5% on a given demand response day, because evaporator coil fan speed increased during the precooling period to facilitate the over-cooling. The resulting increase in evaporator coil fan energy outweighed the savings from increased compressor pumping efficiency at lower SCT from operating at cooler off-peak hours. On systems without evaporator fan speed control, the fan energy increase would not be a factor, and precooling would likely result in a slight net energy savings.

Frozen product storage spaces are good candidates for precooling, in general, because the product can often be cooled somewhat without affecting product quality. Cold storage spaces maintained around 30°F to 35°F present a unique challenge, because the goal in these spaces is often to maintain product as cool as possible without freezing, which would ruin the product. Thus, precooling is not feasible or is very limited. Higher temperature spaces may often be cooled by a few degrees, although the product sensitivity must be considered. There are some products that are vulnerable to chilling injury, but can still tolerate lower temperatures for short durations without serious consequences. Other products are extremely sensitive to chilling injury and should never be overcooled. Examples of products that cannot tolerate overcooling include: cucumbers, cranberries, eggplant, melons, okra, pumpkins, squash, white potatoes, sweet potatoes, and tomatoes, among others (ASHRAE Refrigeration 21.1).

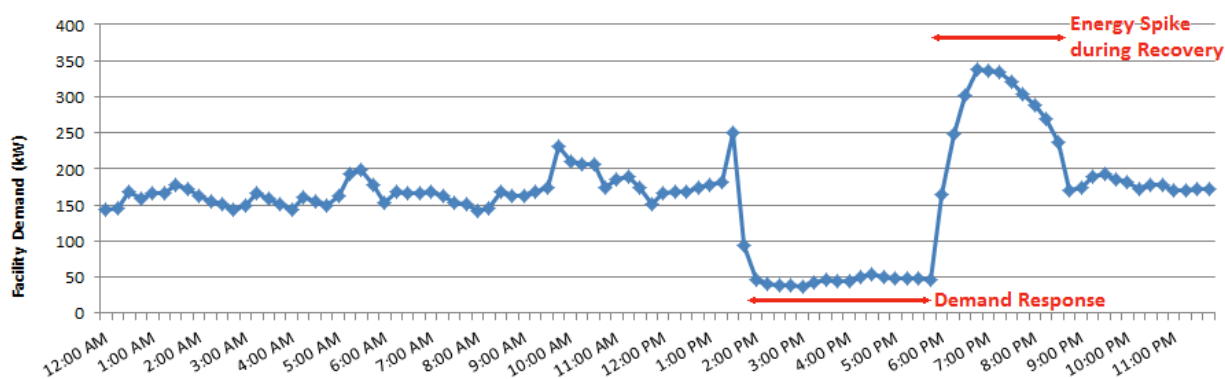
#### ***1.2.1.2 Limiting Refrigeration System Capacity***

Limiting the capacity (and power) of refrigeration equipment, rather than turning it off outright during demand response is an effective way to maintain a baseline level of productive cooling in a refrigerated warehouse, while also achieving reasonable load-shed goals in a demand-response strategy. Because refrigeration systems are designed to handle the peak load during hottest part of the year, they are inherently oversized for the majority of the remaining operating hours of the year. The refrigeration system should therefore be as efficient as possible when operating at reduced capacity to maximize yearly energy savings, and should especially

be efficient at reduced capacity if a demand response strategy that incorporates capacity-limiting is specified.

For refrigeration systems, capacity limiting should occur at the evaporator coils, either through limiting fan speed (or duty cycle for fan-cycling systems), or through turning off select units. Suction group and condenser capacity should be allowed to re-balance with the reduced load. Attempting to directly limit the capacity of the suction group could result in an increase in evaporating temperature in the lowest-temperature space served by the controlled suction group. Discharge air from the evaporator coils would accordingly increase, causing a relative heating effect in the space.

Capacity-limiting logic can also be employed during the recovery period following a demand response event, when the refrigeration system equipment capacity modulates to fully-loaded. Figure 5 shows the spike in demand at a refrigerated warehouse immediately following a demand response event.



**Figure 5: Spike in demand immediately following a demand response event**

For the example warehouse depicted in Figure 5, the spike in demand following the event nearly reached 350 kW, more than double the average daily demand of approximately 160 kW. For warehouses that are on energy tariffs that include high ‘facility’ demand charges (e.g., non-coincident demand charges that apply to the peak monthly demand, regardless of which hour of the day they occur), the cost penalty resulting from setting a new peak demand is potentially significant.

A capacity-limiting control strategy can lessen the magnitude of the recovery period demand spike by spreading the recovery load across more hours. An example capacity-limiting strategy would be to limit the evaporator coil fan speed following the event for all evaporator coils with variable-speed control. The fan speed limit would be subject to a time-delay, and each evaporator coil zone would be released to normal temperature-based speed control in a staggered sequence.

Capacity limiting during the recovery period is a strategy that requires fine-tuning to ensure that the space temperature can be fully pulled down before the following peak-day hours.

Priority is always given to maintaining product integrity first, which may compete with the ability to manage the recovery demand spike if the system lacks adequate capacity to pull down the space temperature in fewer hours with reduced fan speed.

### ***1.2.1.3 Battery Charger Load Management***

Forklift and pallet lift battery chargers can be a large component of peak electrical load in refrigerated warehouses, and can also be a significant source of curtailment for demand response.

A field study was conducted where power meters were installed in three refrigerated warehouses with forklift battery chargers to measure the charger energy usage and demand over a sixty-day period. Each facility had a unique battery charger usage profile. The collected data from the power meters were then used to calculate the energy, demand, and cost from the forklift battery chargers using Southern California Edison's TOU-8 energy tariff. The potential cost savings from shifting the forklift battery charger load to the part-peak hours was also calculated for each facility. Table 3 shows a summary of the data collected for the field analysis.

The field analysis showed that the savings potential from shifting battery charger load from peak hours to mid-peak ranged from 33 to 58%. Further savings would be possible for shifting battery charger demand to the off-peak hours.

To successfully shift battery charger demand, a facility must have an adequate number of battery chargers and batteries available to pre-charge a reserve quantity of batteries for use during demand response. There must also be enough units available to re-charge the packs that were depleted during the demand response event in addition to the units available to handle the typical charging demand.

**Table 3: Summary of battery charger demand and savings potential from shifting load**

Facility	1	2	3
Number of Chargers	23	13	7
Total Installed Charger Amperage	514 Amps	123 Amps	69 Amps
Test period	February 18 - April 29 (One full month, two partial months)	March 4 - May 11 (One full month, two partial months)	March 19 - May 13 (One full month, two partial months)
Maximum On-Peak Charger Demand (kW)	55.54	150.98	22.55
On-Peak Charger Energy (kWh)	7,983	17,320	1,133
Mid-Peak Charger Energy (kWh)	9,160	25,809	1,451
Off-Peak Charger Energy (kWh)	15,823	42,561	1,276
On-Peak Demand Charger Cost (\$)	\$2,416	\$6,854	\$1,141
Charger Energy Cost (\$)	\$5,738	\$14,196	\$681
Total Battery Charger Cost (\$)	\$8,155	\$21,050	\$1,822
Cost Savings from Charging during Mid-Peak Periods (\$)	\$2,681	\$7,170	\$1,052
	33%	34%	58%

## 1.2.2 Load Shedding Strategies

Load shedding is a process of avoiding energy use during on-peak hours altogether. Loads that are “shed” do not need to be “recovered” or made up for later. Five load shedding methodologies described in this section are:

- 1) Lighting Reduction
- 2) Demand Defrost and Defrost Termination
- 3) Infiltration Reduction Strategies
- 4) Turning Off Miscellaneous Equipment
- 5) Increasing Space Temperature Set Point

### 1.2.2.1 Lighting Reduction

Lighting is a simple load to shed during demand response events, because the lights can simply be turned off. Of course, production schedules and general safety will dictate the level to which lighting loads can be shed.

Networked LED lighting technologies exist to govern lighting system behavior at any level of granularity – across an entire facility, zone-by-zone, and all the way down to an individual fixture. The fixtures can operate based on a rule-based profile that takes input from occupancy sensors, ambient lighting conditions, and centralized control. The profile can be interfaced with automatic demand response controls to respond to an event signal from a utility or an aggregator. Quick-starting fixtures such as T8 and T5 fluorescents and LED fixtures can

alternatively be used in conjunction with occupancy sensors that dim (or completely shut off) fixtures when occupancy is not detected.

Regarding lighting curtailment, facility operators should also ask themselves: if a light fixture can be dimmed or shut off for demand response, can it be shut off all of the time? Ideally, all non-necessary lighting should be turned off regardless of whether a demand response event is in effect.

New for the 2014 California Title 24 building energy efficiency standards is a requirement that the total lighting power in buildings greater than 10,000 square feet need to be capable of reducing by at least 15% during demand response events.

#### ***1.2.2.2 Demand Defrost and Defrost Termination***

Defrost load can be shed through the use of technologies that initiate defrost cycles based on the level of frost buildup on the coil (e.g. demand defrost), rather than defrosting based on schedules or run-time accumulation. Temperature sensors on the coil surface can also be used to detect when the frost has been adequately melted from the surface, and terminate the defrost cycle accordingly (e.g. temperature-based defrost termination). These technologies avoid most of the excessive heat that is introduced into a space from scheduled, time-terminated coil defrosts.

#### ***1.2.2.3 Infiltration Reduction Strategies***

Air infiltration into refrigerated spaces represents a significant heat source. During demand response events, there may be opportunities to reduce infiltration air through inter-zonal doorways without severely affecting forklift traffic. Many facilities have adjacent spaces that have several passageways between them, such as from loading docks to the adjacent refrigerated space. During a demand response event, there may be opportunity to simply close a portion of the doors.

For facilities that utilize air curtains, a combination of air curtain and rollup door could be used. The rollup door would kept open during normal operation, and closed during demand response. The air curtain could then be shut off during the demand response event. This strategy has the added benefit that the avoided power demand of the air curtain blower motor would contribute to the demand response curtailment amount.

#### ***1.2.2.4 Turning Off Miscellaneous Equipment***

Facilities with production equipment may have unique, site-specific opportunities to shed electric load by simply turning off equipment that is not in use during peak hours. Examples include:

- Conveyor systems that are not used during peak hours
- Air compressors
- Blast freezers

#### ***1.2.2.5 Increase Space Temperature Set Point***

Increasing the space temperature set point is sometimes proposed as a method for load shedding during demand response. This method is effectively similar to shutting down the refrigeration system—the refrigeration compressors simply turn off (or reduce capacity if serving other refrigeration loads) until the space temperature rises to the new higher set point, at which time the compressors will turn back on. The evaporator coil fans either remain on at 100% speed (if the facility lacks fan control), or reduce to minimum speed or duty cycle.

This method prioritizes space temperature control over participating in the demand response event for any specific duration. The refrigeration system electric demand will return to normal levels when the compressors turn back on, which might occur before the end of the demand response event is declared. Building operators should select a demand response program that provides sufficient contract flexibility to avoid high penalties if the facility ends their participation should the refrigeration system turn back on before the event is over.

Successful implementation of this strategy requires an understanding of the unique air temperature profile in each of the refrigerated spaces, as well as the unique relationship of air temperature to product temperature in the individual spaces. Common warehouse design uses zone temperature sensors for evaporator coil control directly behind the coils, which presupposes that the average space temperature is equal to the average temperature of the air returning to the coil. This is a generally valid assumption for most spaces with good air circulation, and is accurate enough for evaporator coil and space temperature control. However, it likely does not accurately represent actual space air temperature when the air circulation is reduced, and certainly does not represent the product temperature. Moreover, the sensor reading provides no insight about the potential for localized hot spots within the space. If space temperature control is the top priority, then operators can consider allowing the fans to remain on at reduced speed. This will keep some air circulating across the zone temperature sensor so that it is more representative of the actual space temperature (and provides air circulation in the space while avoiding high fan heat). Speeds as low as 30%-40% can be used, which will greatly reduce fan power, while still providing air movement in the room and across the temperature sensor.

### **1.2.3 Energy Efficiency and Demand Response**

As described in Appendix A, many energy efficiency measures are control enhancements that deliver better part-load system efficiency (such as variable speed drives), which inherently offer more control over the refrigeration system (which lends itself to demand response). Most energy efficiency measures also reduce the peak system demand, which is the stated goal of demand response. Some of the most common energy efficiency measures for refrigerated warehouses are listed in Table 4.



**Table 4: Energy efficiency measure implications for demand response**

<b>Energy Efficiency Measure</b>	<b>Implications for Demand Response</b>
Infiltration Barriers	<ul style="list-style-type: none"> <li>• Reduces infiltration, which is the most significant contributor to hot spots when refrigeration is off or reduced</li> <li>• A portion of inter-zonal doors may be temporarily closed during demand response hours for further reductions in infiltration.</li> <li>• Training is required so that forklift operators do not leave doors open, or open doors unnecessarily during demand response events</li> </ul>
Efficient Lighting and Lighting Controls	<ul style="list-style-type: none"> <li>• LED and T5/T8 fluorescent lighting uses less energy and radiates less heat than high-intensity discharge (HID) fixtures.</li> <li>• Occupancy sensors and/or networked controls allow further reductions in load during demand response events.</li> <li>• If pallet racking is high enough, product could be placed near light fixtures, which is warmer than the surrounding space during demand response events</li> </ul>
Condenser Sizing	<ul style="list-style-type: none"> <li>• Oversized condensers save compressor energy and reduce demand by reducing average refrigeration saturated condensing temperature</li> <li>• Pulldown and recovery times after a demand response event are shortened due to increase in refrigeration system capacity from reduced lift</li> </ul>
Compressor Variable-Speed Control and Compressor Sequencing	<ul style="list-style-type: none"> <li>• Part-load suction group efficiency improvement from compressor speed control and supervisory compressor sequencing further reduces demand if used in conjunction with a capacity-limiting demand response strategy</li> <li>• Training required to prevent manual-override compressor sequencing, which can lead to multiple machines running at part-load</li> </ul>
Variable-Speed Evaporator Coil Fan Control	<ul style="list-style-type: none"> <li>• Permits capacity-limiting demand response control strategies</li> <li>• Can be used to control demand spike following a demand response event</li> </ul>
Demand Defrost and Defrost Termination	<ul style="list-style-type: none"> <li>• Can defer defrost for evaporator coils in cooler zones following a demand response event</li> </ul>

### 1.3 Section Summary

Demand response is a set of strategies to manage the demand-side load on the electric grid as a way to balance the supply and demand of electricity. Demand response can be either manually initiated and implemented, manually initiated and automatically implemented (i.e. semi-automatic demand response), or both automatically initiated and automatically implemented (i.e. automated demand response or Auto-DR). Permanent load shifting is a strategy where load is shifted from peak demand periods to off-peak periods on a daily or weekly basis. Refrigerated warehouses offer a unique opportunity to shift a significant amount of demand, but they also present unique system, operational, and control challenges that must be addressed.

In refrigerated warehouses, load-shifting strategies include precooling/overcooling the refrigerated space before a demand response event, limiting the capacity of the refrigeration system by capping the evaporator coil maximum fan speed, and avoiding the usage of forklift/pallet-lift battery chargers during peak periods. Load-shedding strategies include

reducing lighting power, defrosting evaporator coils based on demand and terminating defrost cycles when the coil is sufficiently defrosted, reducing infiltration during demand response periods, and turning off miscellaneous equipment.



## **Section 2. Economics of DR**

### **2.1 Utility Incentives for Energy Efficiency and Demand Response**

All three major California investor-owned utilities (Pacific Gas & Electric, Southern California Edison, and San Diego Gas and Electric) and many of the municipal utility companies serving California communities offer incentive money to offset the cost of energy efficiency and demand response investments. Incentive monies are available for new-construction investments as well as retrofit projects.

#### **2.1.1 Electric Tariff Structures and Demand Response Programs**

Utility companies offer a variety of demand response programs, each with unique curtailment requirements and tariff structures. In general, the financial incentive for curtailing load is higher for programs that have the least notification before the event. Three program types are described below:

- a. Peak Day Pricing and Critical Peak Pricing programs
- b. Demand Bidding and Capacity Bidding programs
- c. Real Time Pricing programs

##### ***2.1.1.1 Peak Day Pricing and Critical Peak Pricing Programs***

Peak Day Pricing (from PG&E) and Critical Peak Pricing (from SCE, also known as Summer Advantage Incentive) are programs with time-of-use based tariff structures. In addition, the tariff structures include significantly higher rates for demand response events. The number of events is contractually limited to approximately 12 per year, and can occur during peak periods, which vary by utility and specific program but are typically defined as a 4-6 hour period sometime between 11 AM and 6 PM on non-holiday weekdays. Participants are notified at least one day before events are called. Some utilities offer structures for participants to earn credits toward bill reductions during non-event hours.

##### ***2.1.1.2 Demand Bidding and Capacity Bidding Programs***

Bidding programs offer participants the opportunity to make monthly nominations (also known as “bids”), of demand reduction, and be reimbursed with payments based on the actual energy or demand reduction when a program event is called. These structures are designed to offer flexibility to adjust the magnitude of the bid and participation preferences every month. Participants can also adjust how many hours of each event they are willing to participate every month (for example, participants may be able to select a 1 to 4 hour window, 2 to 6 hours, or 4 to 8 hours). Utilities typically require participants to place bids prior to the beginning of the month, and may require participants to enroll with a third-party aggregator if they choose to participate in capacity- or demand-bidding programs.

### **2.1.1.3 Real-Time Pricing Programs**

Real-Time Pricing (RTP) structures are intended to set the price of electricity so that they closely mirror the actual wholesale-market cost of energy at the precise time that the energy is consumed. Under these programs, there are no defined “demand response events” called by the utility. Instead, participants monitor the hourly electricity rates and then decide for themselves when it is appropriate to curtail demand. The utilities that offer these rate structures typically provide real-time energy prices on their websites, and also have user-configurable systems to push notifications via email, telephone, or text message to participants when the cost of energy exceeds (or is expected to exceed) user-defined levels.

## **2.2 Demand Response Implementation Cost Case Study**

The following case study shows the actual cost of adding automatic demand response capability to an existing freezer storage facility. The facility was originally built in the 1960s, but the refrigeration system been periodically modernized. The facility stores frozen fish and seafood. Operations are approximately 18 hours per day, 7 days per week. The facility consists of approximately 61,200 square feet of 0°F freezer space and 6,000 square feet of 39°F cooler space. The refrigeration system is a single-stage, built-up central ammonia system with two screw compressors with slide valve unloaders: one 450 HP and one 650 HP. The control system consisted of a central programmable logic controller (PLC).

The average facility demand during the summer on-peak hours is shown in Table 5.

**Table 5: Peak and average demand during summer on-peak hours**

<b>Hour Ending</b>	<b>1:00 PM</b>	<b>2:00 PM</b>	<b>3:00 PM</b>	<b>4:00 PM</b>	<b>5:00 PM</b>	<b>6:00 PM</b>
<b>Average Demand (kW)</b>	418	399	410	393	391	388

Facility management determined that the refrigeration system compressors, condenser, ammonia recirculating pumps, and evaporator coil fans could safely and feasibly be shut off during a demand response event. An independent audit of the select facility loads determined that an average of 173 kW could be shed during a demand response event by shutting off the selected equipment. A new electric panel with an OpenADR-compatible client was added to connect the facility’s existing refrigeration control system to the utility demand response server to automatically receive demand response signals. In addition, the legacy control panels were replaced on both refrigeration compressors to improve control sophistication as well as increase reliability, thereby allowing automatic operation. The cost for implementing demand response is shown in Table 6.

The facility qualified for a utility-sponsored incentive for automatic demand response. The incentive program offered \$300 per kilowatt of average demand reduction. At 173 kW, the incentive was therefore \$51,971. In this case study, the difference between the project cost and the incentive amount was paid for by the customer. In many cases, the utility incentive amount

covers the entire cost of the auto-DR implementation project, with no out-of-pocket cost to the customer.

**Table 6: Automatic demand response implementation cost**

Item	Total Cost
Analysis and Utility Incentive Application Labor	\$8,200
Compressor micro panels	
<i>Equipment</i>	\$17,900
<i>Installation</i>	\$6,000
OpenADR Client and Electrical Panel	
<i>Equipment and Installation Materials</i>	\$1,800
<i>Installation</i>	\$2,700
Refrigeration Control System	
<i>Auto-DR Strategy Programming</i>	\$16,500
<i>Start-up, Fine-Tuning, Ongoing Performance Monitoring</i>	\$16,300
<b>TOTAL PROJECT COST</b>	<b>\$64,800</b>

*Note: Sum of itemized costs may not add to total cost, due to rounding*

## 2.3 Energy Efficiency Measure Cost Case Study

The case study is of a frozen food warehouse in the City of Commerce, California. The building owners participated in a utility energy efficiency retrofit incentive program that targeted industrial refrigeration systems with complex built-up mechanical systems. Full turn-key project coordination was provided through the program, which included identification of energy efficiency upgrade opportunities, quantification of the potential energy and operational cost savings, and calculation of the implementation cost of the measures.

- Facility Description
- Energy Efficiency Measures
- Scope of Work
- Economics
- Case Study Conclusions

### 2.3.1 Facility Description

The warehouse consists of seven freezer spaces that are occupied by individual tenants. The ammonia refrigeration system had been upgraded and enhanced several times, but the warehouse envelope is 1960's vintage and remains largely unchanged. The facility includes approximately 70,200 square feet of refrigerated area, including 64,200 square feet of 0°F freezer space, and 6,000 square feet of 39°F cooler space. 400W high-pressure sodium HID lighting was

used in every refrigerated space, with all fixtures remaining on during business hours. The ammonia refrigeration system consists of one 450 HP screw compressor and one 650 HP screw compressor, served by a 2,815 MBH evaporative condenser. The system exclusively serves long-term storage space loads, with no quick-chilling or processing loads.

The original refrigeration controls included individual, proprietary control systems from a vendor who manufactures their own single-board control hardware, with control logic written in a proprietary language. Due to the proprietary nature of the controllers, expanding and improving the controls was difficult. The overall control architecture consisted of standalone controls for each equipment group—one controller for the evaporator coils, one for defrost control, and one for compressor sequencing and condenser control. The both compressors also had local micro-panel controllers for individual capacity control. The overall refrigeration control approach consisted of the following strategies:

- 80°F fixed SCT set point with condenser fan cycling control
- -20°F fixed SST set point
- Evaporator coil fans run continuously, except during defrost, with no speed control and liquid solenoid cycling for space temperature control
- Scheduled defrost strategy with time-clock defrost termination

### **2.3.2 Energy Efficiency Measures**

A comprehensive survey of the facility and operations revealed several energy saving opportunities:

- Control enhancement measures
  - Reduce minimum head pressure from 80°F SCT to 72°F SCT
  - Ambient-following SCT control strategy
  - Variable-speed condenser fan control
  - Variable-speed evaporator fan control
  - Floating suction pressure control
  - Defrost controls to terminate defrost cycle based on temperature instead of timer countdown
- Infiltration Reduction Measures
  - Repair or replace worn-out strip curtains
  - Seal various small openings in the building envelope
- Lighting Measures
  - Convert high-pressure sodium light fixtures to T5HO fixtures
  - Install occupant sensors

### **2.3.3 Scope of Work**

Full implementation of the identified measures required the following action items:

- Demolish existing controls

- Install one main refrigeration control panel, and two remote air unit control panels, which include:
  - 2x 20HP 480V variable-frequency drives
  - 11x 5HP 480V variable-frequency drives
  - 6x 7.5HP 480V variable-frequency drives
  - 3-contactor bypass assemblies, overload protection, and output filters for each VFD
  - Allen Bradley PLC, chassis, power supply, and related input/output and Modbus communications modules
  - 15-minute UPS power supply
- Install 32x 4-20mA space temp probes, 1 ambient temp/RH sensor, 2x pressure transducers
- Power, control, sensor, and conduit subcontracts
- Plant-wide high-efficiency inverter-duty motor replacements
- Configure and install HMI PC
- PLC programming
- Labor and materials to replace strip curtains and seal small openings
- Lighting enhancements via subcontract
- Start-up and system fine-tuning

### 2.3.4 Economics

The annual energy, demand, and cost savings for each individual energy efficiency measure were calculated using DOE-2.2R energy analysis software. Table 7 shows the results of this study. Electric costs are based on electric rates from an appropriate time-of-use (TOU)-based rate schedule that accounts for peak, mid, and off-peak rate variations as well as monthly customer and facility charges. This rate schedule is applicable for sites with demand greater than 500 kW.

**Table 7: Annual energy savings, yearly peak demand reduction, and annual energy cost savings for individual energy efficiency measures**

Measure	Energy Savings (kWh)	Peak Demand Reduction (kW)	Utility Savings (\$)
Floating head pressure, ambient-following controls, variable speed fan control	239,305	15.7	\$24,584
Floating suction pressure	81,628	24.6	\$11,127
Evaporator coil fan variable speed control	510,034	0.0	\$41,581
Lighting retrofit and motion sensors	530,013	74.8	\$65,394
Infiltration reduction measures	16,737	0.9	\$1,464
Defrost control upgrades	18,158	1.4	\$1,600

Note that, because there are interactions between the various energy efficiency measures, the savings cannot be added directly to obtain the “total” savings from implementing all measures

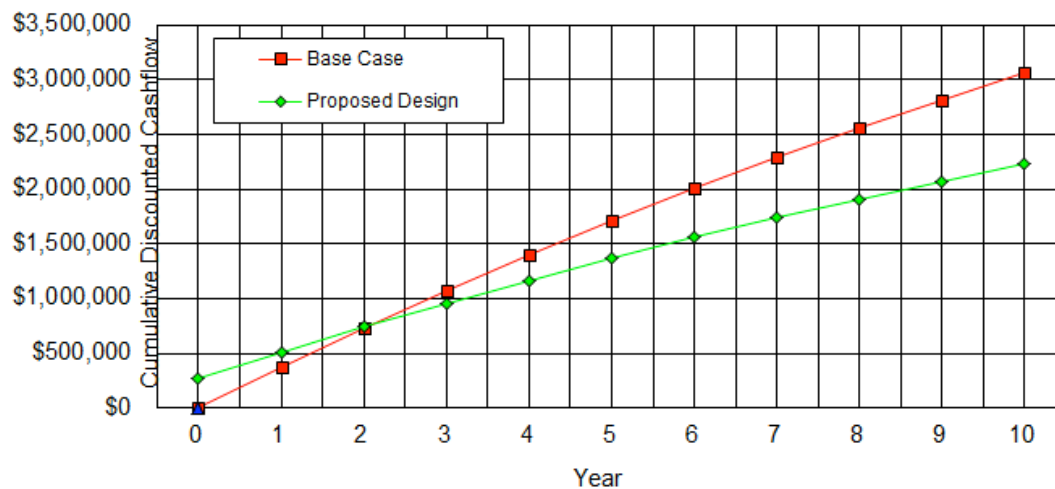


simultaneously. The results are shown for each individual measure in Table 7 to show the relative impact of each measure on the total savings, which are shown below:

<b>Total Utility Savings (kWh)</b>	<b>1,420,695</b>
<b>Base Case Annual Utility Cost</b>	<b>\$405,640</b>
<b>Proposed Design Annual Utility Cost</b>	<b>\$259,500</b>
<b>Annual Utility Cost Savings vs. Base Case</b>	<b>\$146,140</b>
<b>Proposed Design Additional Capital Cost</b>	<b>\$327,020</b>
<b>Utility Incentive</b>	<b>\$151,196</b>
<b>Net Capital Cost after Incentive</b>	<b>\$175,824</b>
<b>Simple Payback (years)</b>	<b>2.5</b>
<b>Net Present Value</b>	<b>\$1,311,483</b>
<b>Internal Rate of Return</b>	<b>85%</b>

### 2.3.5 Case Study Conclusions

The energy efficiency project resulted in an annual savings of 1,420,700 kWh and \$146,100 per year. The implementation cost totaled \$327,020, which was offset by a utility incentive of \$151,196, resulting in a simple payback less than three years. Figure 6 shows the cumulative discounted cash flow for the energy efficiency project, versus the base case.



**Figure 6: Cumulative discounted cash flow for the energy efficiency enhancement project described in Case Study #1**

## 2.4 Section Summary

The cost of adding demand response capability to a refrigerated warehouse can vary widely, depending of the type of demand response being implemented (automatic versus manual, for example), and the type and vintage of the existing refrigeration equipment and control system. Utility incentives for demand response (particularly automatic demand response) may account for all of the implementation cost.

Energy efficiency enhancements can significantly reduce annual operating costs for refrigerated warehouses. The cost of implementation is sufficiently low, and utility incentives are sufficiently high, that the simple payback is often between 2 to 4 years for energy efficiency upgrades.

## Section 3. Performance with DR Measures

### 3.1 Field Studies

Field studies were conducted at several different refrigerated warehouses in California, in which air temperature and product surface temperature were measured before, during, and after simulated demand response events. The analysis explored the role played by air temperature, product mass, building mass, and various construction features on the space temperature during steady-state operation, and the temperature rise during demand response events.

Several of the elements discussed in Section 1.2 were chosen for field study, based primarily on opportunity from the mix of warehouses where operators agreed to participate, as well as feasibility of evaluating the element with the monitoring equipment used. Table 8 shows the elements that were examined in this field study.

**Table 8: Demand response considerations and load-shifting/load-shedding strategies explored during field studies**

Considerations			
Facility	System	Control	Operations
I. Lighting	I. Condenser Sizing	I. Evaporator Fan Speed	I. System Maintenance
II. Infiltration	II. Evaporator Coil Sizing and Selection (air throw)	II. Compressor Part-Load Efficiency	II. Product Distribution
III. Underfloor Heating Systems	III. Overall System Design	III. Defrost Considerations	III. Performance Monitoring
		IV. Space Temperature Variability	

Strategies	
Load Shifting	Load Shedding
I. Precooling	I. Lighting Reduction
II. Capacity Limiting	II. Demand Defrost
III. Battery Charger Load Management	III. Underfloor Heater Control
IV. Defrost Scheduling	IV. Infiltration Reduction Strategies
	V. Turning Off Miscellaneous Equipment
	VI. Increasing Space Temperature Setpoint

The analysis also investigated which warehouse usage characteristics, maintenance circumstances, and design features combined to produce local areas of relatively warm air during steady-state operation, and/or contribute the most to space temperature rise during demand response events. Factors such as air circulation, space geometry, construction vintage, infiltration air volume and management tactics, and evaporator fan speed were analyzed. The effect from these factors, and others, are summarized in this section and described in detail in Appendix B.

In this analysis, effort was made to specifically target the areas within each test space where the temperature was expected to be the most affected when refrigeration was shut off during a demand response event. In general, the temperature gains at the peak of the simulated demand response events are likely tolerable for the types of product stored in the “field study” warehouses. With some exceptions (namely direct outside air infiltration into a freezer space), individual influencing features did not typically result in high gains in space temperature. Rather, the highest gains in temperature, where the peak temperature may be deemed too excessive to participate in demand response, were observed where two or more influencing features were present. Examples included:

- Case Study #1, space 1. At this warehouse, the evaporator coil closest to the entry vestibule to the space was down for maintenance. The combination of close proximity to the entry vestibule, a heat source (radiative heating lamps in the vestibule), and low circulation (due to the inoperable evaporator coil) resulted in a temperature of almost 8°F above the space temperature set point during normal (steady-state) operation, and a further gain of 3°F at the peak of the demand response event.
- Case Study #2. Here, the combination of low circulation (a result of pallets stacked directly in front of the coil) and very high levels of unconditioned outside air infiltration resulted in a local space temperature of almost 6°F higher than the space temperature set point during steady-state operation, and a further gain of 15°F at the peak of the demand response event.

This study shows that the largest single contributor to temperature gain during demand response is infiltration air, either from the outdoors or from adjacent spaces that are controlled to a higher temperature. The magnitude of the temperature gain from infiltration varied based on the type of infiltration barrier used, the volume of traffic through the passageway, and the temperature difference between the test space and the adjacent space.

In general, the rate of temperature rise at any given point within a space is mostly uniform throughout the space when refrigeration is turned off, unless a significant source of heat (such as a doorway) is present. Factors such as lighting (and proximity to lighting fixtures), heat gain from interior surfaces—even south-facing, exterior surfaces and roofs—and buoyancy-driven stratification did not significantly affect the space temperature. Note that the analysis revealed that some of these features did locally affect space temperature, but the effect was mostly not significant.

Because temperature rise is mostly uniform throughout the space, it is important for the steady-state temperature in the space to also be uniform. Good air circulation coincided with even steady-state temperatures. The second test space at Case Study #1 had the lowest average deviation (0.4°F), and second lowest maximum deviation (2.5°F) from space temperature set point of any of the case studies. The largest recorded difference in any two sensors was also the lowest at Case Study #2 than at any other test space, at approximately 4.6°F. No discernable correlations could be found between temperature and height, or proximity to walls, roof, or

lighting fixtures at this space. Air circulation in this space was very good, with consistent air movement at all tested locations.

As a general observation, warehouses where the evaporator coil throw direction is parallel to the pallet racking tended to have better overall air circulation throughout the space, which led to more uniform space temperature during steady-state operation. In all of the warehouses that had this configuration, the air units and pallet racks were arranged such that each aisle between the pallet racks was served by at least one air unit. Arranging the pallet racks and coils this way also avoids the possibility of stacking pallets in front of the air unit, which was found to shorten throw length, disrupt air circulation, and contribute to non-uniform space temperatures.

Variable-speed evaporator coil fan control provides an option to limit the coil fan speed during demand response events, significantly reducing fan power while also maintaining a baseline level of air circulation and productive cooling in the space. The temperature rise during demand response events may be limited, or possibly even completely mitigated, by allowing the fans to run at reduced speed. Some building designers hesitate to implement variable-speed fan control in refrigerated spaces, because they believe that air circulation will be inadequate at reduced speed to prevent the formation of localized areas of warm air. For this test, no local hot spots were found when fan speeds were limited, even in the areas furthest from the evaporator coil. The test affirms the validity of variable-speed evaporator coil fan control as an energy efficiency measure, and shows how variable-speed can create strategic options for building operators who are constructing a demand-response strategy.

## **3.2 Energy Model Analysis**

Hourly simulations were utilized for two locations to further investigate demand response elements and considerations that the field study could not capture. The elements that are summarized in this section and described in detail in Appendix C were primarily chosen for analysis because they could not be evaluated via field study, including:

- a) Permanent Load Shifting and Demand Response on Consecutive Days
- b) Precooling Analysis
- c) Effect of Building and Product Mass

Whole-building energy models were constructed to evaluate the energy and cost impacts of both demand response and permanent load-shift control strategies. The modeling software used for this analysis is DOE-2.2R. DOE-2.2 is a sophisticated component-based energy simulation program that can accurately model building envelope, lighting systems, HVAC systems, and refrigeration systems. The 2.2R version is specifically designed to include refrigeration systems, using refrigerant properties, mass flow and component models to model refrigeration system operation and controls system effects.

The two energy models are based on Test Space #1 and Test Space #2 at the refrigerated freezer warehouse in Buena Park, California, that was evaluated in Case Study #1 of the field analysis

presented in Appendix B. The energy models were calibrated using performance data collected by the refrigeration control system, as well as refrigerated space temperature data collected during field analysis.

In summary, refrigeration systems may require 24 hours or more to completely recover from a demand response event. If a system participates in demand response on two or more consecutive days, the temperature rise of each consecutive demand response event may be greater than the previous day. If a facility utilizes a permanent load-shift control strategy, the system daily peak load and daily peak space temperature rise will re-balance and a higher steady-state value.

The maximum space temperature during demand response or load-shift events is significantly curtailed by precooling (e.g. over-cooling the product before a demand response event), but the magnitude of the range in space temperature is generally not affected. The duration of the recovery period after a demand response event is inversely proportional to the time spent precooling before the event, but the average fan speed (and the consumed power) is higher with the precooling strategy, because fans are at full-speed during precooling hours.

Building mass and stored product temperature greatly influences the total space temperature rise during a demand response event, because the building and product mass absorb the majority of the heat flux into the space during demand response.

## **Section 4. Identifying Facilities Suited to DR**

### **4.1 Technical Suitability of Facilities for Demand Response**

Assess the technical suitability of facility controls systems, level of automation and equipment for DR participation. The contractor shall tie into past studies and provide detailed descriptions of how these criteria need to be assessed, including at least the following:

#### **4.1.1 Facility Type**

Different facility types have varying advantages and challenges related to demand response capability. This section specifically examines the following four facility types:

- a. Frozen storage warehouses
- b. Perishable storage warehouses
- c. Controlled-atmosphere facilities
- d. Grocery distribution centers
- e. Combined processing/cold storage facilities

##### ***4.1.1.1 Frozen Storage Warehouses***

Frozen storage warehouses are facilities where nearly all refrigeration system capacity serves frozen storage space. These facilities usually receive product at, or near, the storage temperature, and pulling sensible heat out of the product is not necessary. Due to the thermal mass of the stored product, these sites are ideal candidates for demand response.

##### ***4.1.1.2 Perishable Storage Warehouses***

Perishable storage warehouses store products that have finite shelf lives, such as unfrozen meat, poultry, fish, milk, eggs and many raw fruits and vegetables. Product is typically only stored for a few days, which means that perishable storage facilities tend to have higher average infiltration loads, as well as higher forklift and worker traffic than frozen storage warehouses. Product temperature is also a bigger concern in these facilities. A realistic demand response strategy for these facilities would be to limit evaporator fan speeds rather than shutting off zones entirely.

##### ***4.1.1.3 Controlled-Atmosphere Facilities***

Controlled-atmosphere facilities specialize in the long-term storage of produce, which is largely achieved by strict space temperature controls as well as control of oxygen levels and other factors to extend product life. Such facilities may be less able or willing to reduce demand by deferring cooling.

##### ***4.1.1.4 Grocery Distribution Centers***

The refrigerated warehouse portions of grocery chain distribution centers turn product over very rapidly, compared to other facility usage-types. Some facilities will turn more than 90% of

the total stored product in a 24-hour period. Such facilities have significant refrigeration load related to infiltration and forklift and worker traffic. Due to the nature of the facility and the business, these loads cannot be shifted by deferring shipping schedules. Like perishable storage warehouses, distribution centers may benefit most from limiting evaporator fan speeds and keeping refrigeration compressors on for demand response, rather than completely shutting off all refrigeration capacity. .

#### ***4.1.1.5 Combined Processing/Cold Storage Facilities***

Facilities with combined processing and cold storage usually have, at a minimum, the same opportunities to reduce demand in their cold storage areas as pure cold storage warehouses. The majority of the refrigeration power demand is often associated with process cooling loads at these facilities, so any demand response curtailment is likely to come from the evaporator coil fans in the cold storage warehouse. Additional savings would come from the refrigeration compressors, whose capacity and power usage would re-balance with the reduced load.

### **4.1.2 Product Stored**

The type of product stored at a refrigerated warehouse may influence the level to which demand response can be practiced. This section specifically examines the following three product types:

- a. Frozen Food
- b. Cold Storage
- c. Beverage Facilities

#### ***4.1.2.1 Frozen Food***

Spaces with frozen product are excellent candidates for demand response strategies. Due to the thermal mass of the stored frozen product, as well as the thicker insulation associated with freezer spaces, they can often curtail load for a longer duration than cooler spaces. Frozen product storage spaces are good candidates for precooling as well, as there is essentially no lower limit to how cold the product can get.

#### ***4.1.2.2 Perishable Products***

Spaces maintained between 25°F and 35°F present a unique challenge for demand response. The target storage temperature for these products is set low enough to maximize product longevity, but high enough to avoid chilling injury. There are some products that are vulnerable to chilling injury, but can still tolerate lower temperatures for short durations without serious consequences. Others are extremely sensitive to chilling injury and should never be overcooled. Examples of products that cannot tolerate overcooling include: cucumbers, cranberries, eggplant, melons, okra, pumpkins, squash, white potatoes, sweet potatoes, and tomatoes, among others (ASHRAE Refrigeration 21.1).



#### **4.1.2.3 Beverage Facilities**

Facilities that store beverages can typically shed demand for very long periods, due to the high thermal mass and specific heat of the stored product, the facility can usually tolerate long demand response durations.

### **4.1.3 Control Systems and Level of Automation**

The minimum amount of control for demand response is subjective and dependent on the goals of the demand response strategy as well as the state of the existing system. Large, custom built-up refrigeration systems usually require integrated control systems or partially PLC-controlled systems to safely and reliably participate in demand response activities. Fully integrated control systems can be used to schedule load reductions in an organized manner. A system with PLC control of evaporators (but standalone controls on compressors and condensers) can often reliably reduce demand by scheduling off the evaporators using the PLC, and relying on the standalone controls for compressors and condensers to eventually turn off the equipment when sufficient load has dropped.

Most facilities have some demand response potential (other than the refrigeration system) that is relatively low-cost to automate, and does not require an integrated control system. Many times, a simple relay panel with a micro-controller could be used to interrupt certain lighting circuits, battery chargers, or other curtailable loads in response to a demand response signal.

Facilities often have curtailable loads that require different amounts of advanced notification. Certain actions could have very short (four minute or less) response times, such as adjusting lighting levels or evaporator fan speeds. Other actions would require more lead time. Maximizing the demand response potential of a given facility will likely benefit from a tiered approach that includes both Automatic and manual demand response strategies.

### **4.1.4 Equipment**

Industrial refrigeration systems found in refrigerated warehouses and production facilities are typically one of these three types:

- a. Split Systems
- b. Parallel Rack/Packaged Skid Systems
- c. Custom Built-Up Systems

The type of refrigeration system dictates the opportunities for demand response.

#### **4.1.4.1 Split Systems**

Split systems consist of a condensing unit (a condenser and one or more compressors on a common chassis) and one or more associated direct-expansion evaporators located remotely from the condensing unit. These systems often have limited ability for capacity modulation and frequently utilize on/off controls. For these units, the only option for demand response may be to shut off the system during the event. Some larger condensing units, however, may feature compressor unloaders or even continuously variable compressor capacity modulation devices,

which would permit variable-speed evaporator coil fan control. For these units, there may be opportunity to reduce capacity for demand response if the control system is sufficiently sophisticated.

#### ***4.1.4.2 Parallel Rack/Packaged Skid Systems***

Parallel rack/package skid systems are halocarbon systems that typically utilize small screw compressors or semi-hermetic reciprocating compressors in a parallel configuration. Most often, they serve direct-expansion evaporators. Parallel systems inherently have more steps of capacity and may have unloading capability on individual compressors. They typically range from 50 BHP to 500 BHP of total compressor power. It is more common to see controls for energy efficiency (such as floating head pressure, floating suction pressure, and variable speed evaporator fan control) on these systems compared to split systems.

There are typically ample demand response opportunities for parallel rack systems. However, the control system is likely to be an integrated control system with proprietary hardware/software that would require assistance from the controls provider to interface the unit with an OpenADR client or implement demand response programming.

#### ***4.1.4.3 Custom Built-Up Systems***

In customized built-up systems, equipment such as evaporators, compressors, and condensers are selected individually and integrated by a system designer who also sizes the interconnecting piping and valves. The system components are then assembled in the field. Because the system is customized, the controls are also customized. Due to the higher initial cost of a custom system, they are most often larger systems (300 BHP to over 10,000 BHP of compressor power). While smaller systems may use halocarbon refrigerants, larger systems frequently (but not always) use ammonia as the primary refrigerant.

Not surprisingly, custom built-up systems exhibit the widest variability in system and control configuration. Options for demand response, and the magnitude of the demand response potential, are typically the greatest for these system types. However, the level of control modifications, and safety precautions (especially if the system uses ammonia refrigerant) are also the highest for this system type.

## **4.2 Considerations for Demand Response**

Industrial refrigerated warehouses are excellent candidates for implementing demand response. However, several different elements must be considered when gauging the feasibility of implementing a demand response strategy. This section covers the following topics:

- a) Facility, System, Control, and Operational Considerations
- b) Practical Considerations

## 4.2.1 Facility, System, Control, and Operational Considerations

This section presents the most important aspects of a refrigerated warehouse that must be considered if demand response is to be implemented. Table 9 lists the topics covered in this section.

**Table 9: Facility, system, control, and operational considerations for demand response**

Demand Response Considerations							
Facility		System		Control		Operations	
I.	Lighting	I.	Condenser Sizing	I.	Evaporator Fan Speed	I.	System Maintenance
II.	Infiltration	II.	Evaporator Coil Sizing and Selection (air throw)	II.	Compressor Part-Load Efficiency	II.	Product Distribution
III.	Underfloor Heating Systems			III.	Defrost Considerations	III.	Training
				III.	Overall System Design		

### 4.2.1.1 Facility Considerations

There are several facility-related elements in a refrigerated warehouse that must be considered when assessing feasibility of implementing a demand response strategy in a refrigerated warehouse. This section takes a closer look at the following elements:

- a. Lighting Considerations
- b. Infiltration Considerations
- c. Underfloor heating systems

#### 4.2.1.1.1 Lighting Considerations

All lighting energy in a refrigerated space eventually becomes heat energy. Because the lights cannot be completely turned off without significantly affecting warehouse production, the lighting system represents a persistent load that, in the absence of any curtailment effort, can contribute to swings in space temperature when the refrigeration system is turned off during a demand response event.

Fluorescent and LED lights are preferred over high-intensity discharge (HID) fixtures such as metal halide, high-pressure sodium, and mercury vapor lamps, for two primary reasons:

1. Fluorescent and LED lights are more efficient, meaning they radiate significantly less heat than HID fixtures (in addition to the self-evident advantage of consuming less electric energy and reducing demand)
2. HID fixtures take up to 10 minutes to ramp up from off to full brightness, and cannot be quickly switched off and on. HID lights are therefore not suitable for use with control devices such as occupancy sensors.

Lighting energy is relatively simple to curtail during demand response events. Assuming the light fixtures are fluorescent or LED, a portion of the lights can simply be turned off. For automatic demand response, the lighting system can be networked to reduce demand based on an input from a PLC or centralized control system, with no human intervention. Occupancy sensors are also an attractive control method, from both a demand response and energy efficiency perspective.

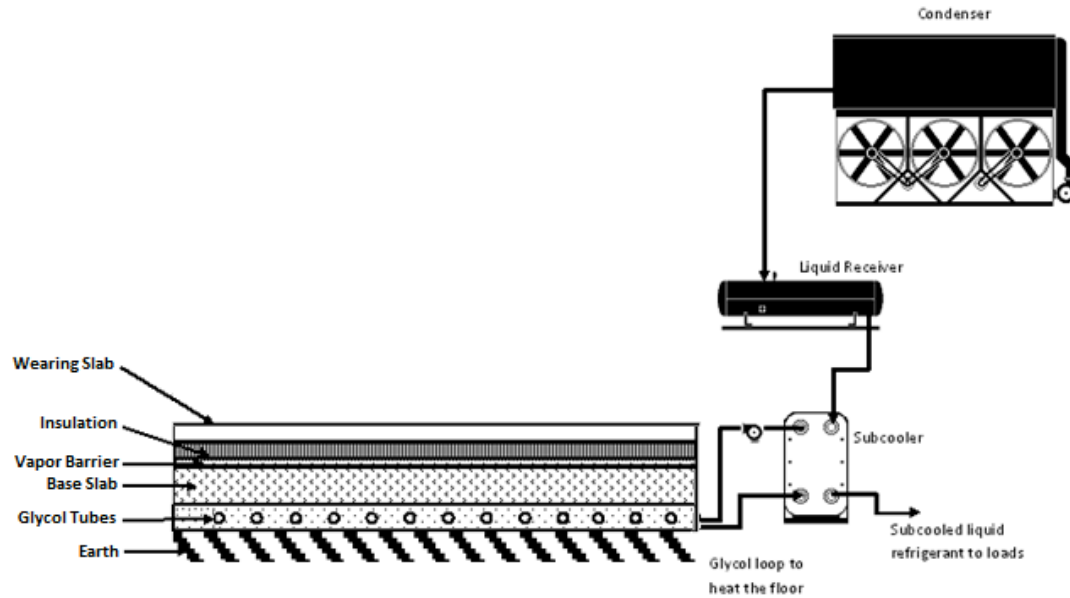
#### **4.2.1.1.2 Infiltration Considerations**

Infiltration air, either from the outdoors or from adjacent spaces that are controlled to a higher temperature, contributes as much as 80% of the load within a space (Wylie & Scott, 2013). Infiltration air can also concentrate in “hot spots” of local warm air, diminishing the demand response potential in the space, and jeopardizing product integrity. A strategy for managing infiltration air is therefore considered essential in an overall approach to implementing demand response.

#### **4.2.1.1.3 Under-Floor Heater Considerations**

In California, the current (2013 version) Title 24 energy efficiency standards already require electric-resistance underfloor heaters to be shut off during summer on-peak hours. The heaters should also be shut off during any hour of a demand response event to avoid adding heat to the space when the refrigeration is off. For automatic demand response, this means the heater controls must be interfaced with the refrigeration control system or otherwise made capable of responding to a signal from the utility or demand response aggregator.

Electric resistance heaters are not energy efficient. A more energy-efficient alternative is to use heat from the suction group discharge via a heat exchanger connected to a glycol loop that circulates glycol under the freezer slab. An even more efficient alternative is to actively sub-cool the refrigerant via a heat exchanger connected to a glycol loop. Figure 7 shows a system configured to heat a freezer underfloor by sub-cooling the liquid refrigerant.



**Figure 7: Under-floor heating via refrigerant sub-cooling**

This configuration saves energy not only by avoiding the penalty incurred by using electric resistance under slab heaters, but also by increasing the net effectiveness of the refrigeration system.

#### **4.2.1.2 System Considerations**

There are several system-related elements in a refrigerated warehouse that must be considered when assessing feasibility of implementing a demand response strategy in a refrigerated warehouse. This section specifically examines the following elements:

- a. Condenser Sizing
- b. Evaporator Coil Sizing and Selection
- c. Overall System Design

##### **4.2.1.2.1 Condenser Sizing**

For demand response, the condenser capacity influences the overall refrigeration system performance during the post-event recovery period after a demand response or load-shed event. During this period, the refrigeration system can operate at a smaller average temperature difference (TD) between the ambient temperature and a lower saturated condensing temperature (SCT) if the condenser capacity is larger.

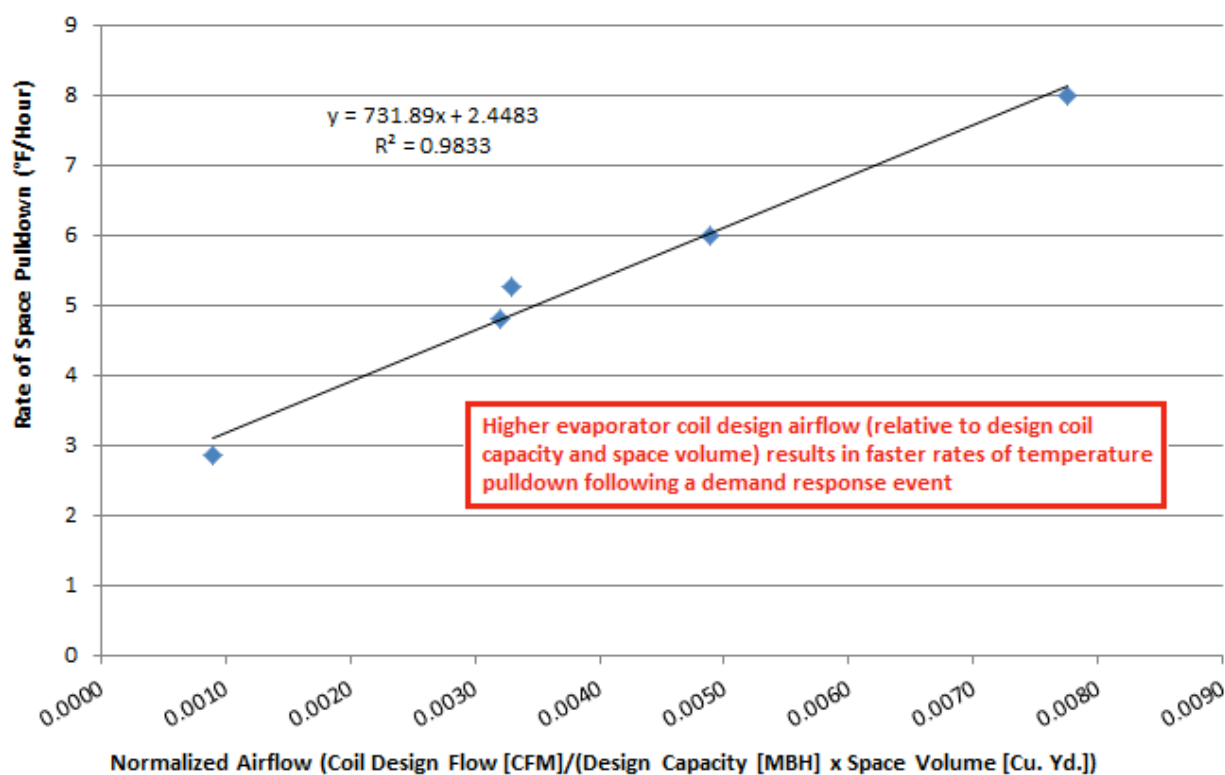
Lowering the SCT reduces the compressor lift and increases the compressor pumping capacity. With higher pumping capacity, heat is removed from the refrigerated spaces in less time, which improves product integrity, and increases the number of hours that evaporator coil fans can

operate at reduced speed where they are most efficient. Having a lower SCT during recovery periods also means that the spike in demand after a demand response event will be lower.

#### 4.2.1.2.2 Evaporator Coil Sizing and Selection

Evaporator coil sizing and selection has a big impact on a building's ability to participate in demand response events.

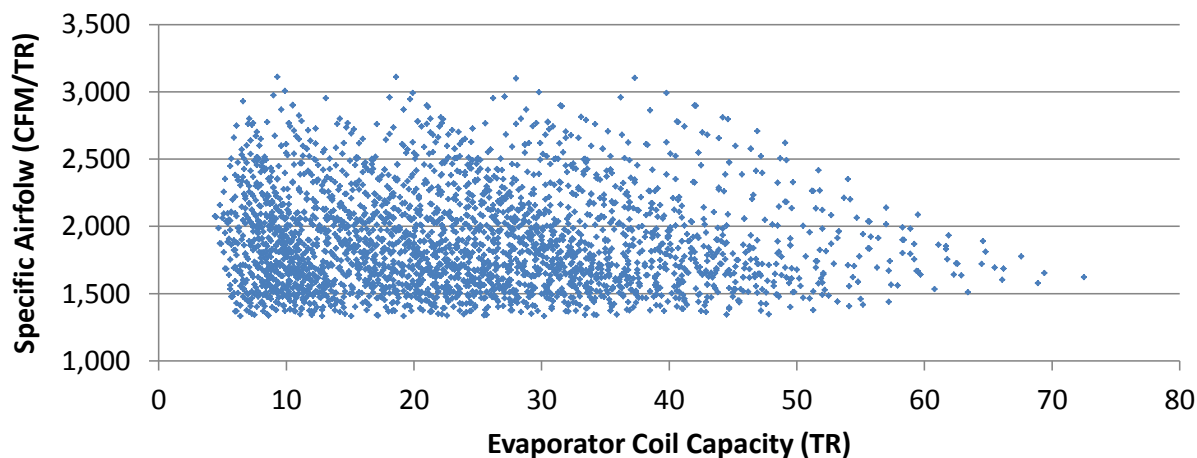
The evaporator coils' airflow should also be considered if demand-response capability is a design criterion. Care must be taken to select units that balance evaporator efficiency with air flow volume, which may be inversely-related parameters. Evaporator coils with higher airflow circulate more air and can pull down the temperature of a refrigerated space faster than coils with low air flow. Figure 8 shows the relationship between the rates of recovery (in °F per hour following a demand response event) versus normalized airflow (total evaporator coil airflow volume divided by design capacity, divided by refrigerated space volume). Data were collected from performance monitoring software using refrigeration system controller data from five refrigerated warehouses.



**Figure 8: Rate of Recovery versus Capacity/Volume Ratio**

Figure 8 shows that refrigerated spaces with more airflow relative to evaporator coil capacity and space volume have a higher rate of temperature recovery than spaces with less airflow volume.

Evaporator coils are available in a wide range of catalog capacities. Due to variations in fin density, row depth, face area, and fan size, a manufacturers catalog will often list two or more models with identical capacities. The airflow for each model may vary significantly. Figure 9 shows the variation in evaporator coil airflow volume versus catalog capacity for seven of the largest refrigerated warehouse evaporator coil manufacturers serving the United States.



**Figure 9: Evaporator coil specific airflow versus capacity for all catalogued models**

Figure 9 illustrates that for any given cooling capacity the variation in airflow volume in the available models is quite large.

For refrigerated spaces, there is no industry-standard design practice for definition of space airflow volume like there is for HVAC design. Whereas HVAC system designers consider both the cooling capacity and air circulation requirements for a space (i.e. with a determination supply air temperature), refrigeration cooling coils are often bought based on cooling capacity and cost alone, with airflow volume seldom examined as an independent design parameter. Excluding spaces where humidity control is a project requirement, airflow considerations typically only relate to the air “throw” length. Airflow is a key concept related to demand response, and justifies greater future attention. Developing better airflow design in refrigerated spaces can result in better temperature performance, improved efficiency and facilitate increased demand response participation.

On the topic of the evaporator coil energy efficiency in relation to airflow, there are considerations beyond just coil capacity, motor input power, and CFM capacity. It is generally understood that there are different airflow requirements depending on the load served—a produce cooler with high respiration load and product turn-over would require a much higher turnover rate than a cheese storage cooler, for example. Low-temperature coils with wider fin spacing and design for frosted coil operation and longer intervals between defrost would understandably have lower air unit efficiency than a coil designed for non-frosted operation. Also, coils in applications with external static pressure or longer throw requirements would be expected to have higher fan power. Finally, load profiles are generally different depending on

the load served as well. All of these considerations must be balanced to select the optimum evaporator coil for any given facility, in addition to the importance of having good airflow, should the design requirements call for demand response capability.

On the topic of defrost, evaporator coils need to be able to operate for longer durations between defrosts with demand response. Heightened engineering scrutiny should be given to coil fin spacing as well as the design temperature difference (TD) between saturated evaporating temperature and space temperature, to ensure that the coils are capable of deferring defrosting until after space temperatures have recovered from a demand defrost event. Lower design TDs and wider fin spacing permit extended coil operation between defrosts. Sources of latent heat should also be identified and effort should be made to reduce their impact, if possible.

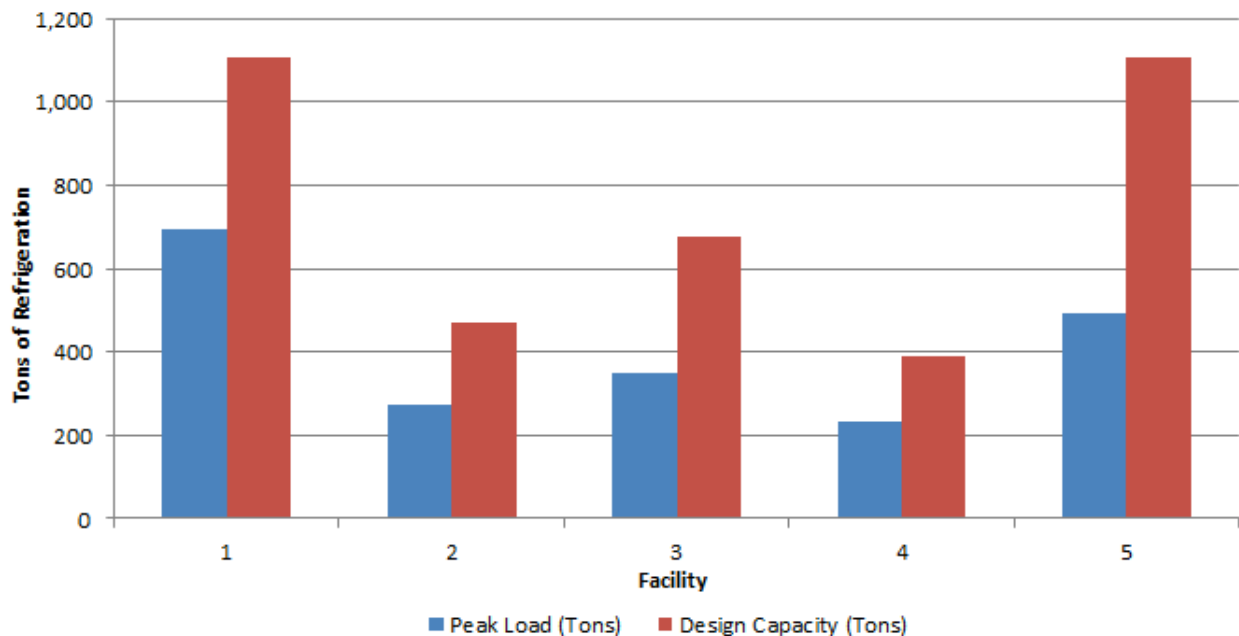
#### **4.2.1.2.3 Overall System Design**

A thorough understanding refrigeration system loads is required before Demand Response capacity can be a “designed-in” specification in a refrigeration system.

Refrigeration systems must always meet the cooling load and maintain space temperature, because nearly all installations serve perishable or frozen food products that must be maintained within a safe temperature range. Accordingly, the design load often includes an excessive safety factor. Current practice for establishing refrigeration design loads usually involves totaling the peak expected load from all anticipated load sources (maximum expected product pull-down and respiration loads, thermal conduction through the envelope calculated on the peak design hour of the year, lighting system load with all lights on continuously, maximum expected infiltration load, maximum expected forklift and worker traffic etc.), and then applying a generous safety factor to arrive at the design load. High safety factors are also often employed because owner’s project requirements (OPRs) are not well defined.

Because not all heat loads are coincident, and because the magnitude of the loads is very seldom near the peak design value, refrigeration systems are frequently oversized. Figure 10 shows the refrigeration system design capacity versus actual yearly peak load for five refrigerated warehouses.





**Figure 10: Peak annual load versus design capacity for five California refrigerated warehouses**

As demonstrated in Figure 10, the peak yearly refrigeration system load is often significantly less than the design load—in some cases it is less than half.

Demand response capability inherently requires more refrigeration system capacity, versus a system where demand response is not included in the design criteria, because the system must be sized to handle the load in fewer hours. Due to over-sizing inherent in current design practice, many systems are “accidentally” capable of reasonable levels of demand response. However, specifying even more capacity for demand response will result in even higher levels of oversizing, wasting investment capital on unnecessarily large equipment. One alternative to peak-load summation or rule-of-thumb sizing calculations is using energy modeling software to right-size equipment, which can accurately account for weather, building mass, infiltration, and explicit loads like lighting, traffic, and miscellaneous equipment.

Deliberate, designed-in oversizing for demand response does not necessarily need to apply to all refrigeration system components equally. Evaporator coils must be purposefully sized to handle the design load during the hottest hours of the year and must be designed to do so in a reduced time period for demand response, with additional reserve capacity as a safety factor. However, refrigeration system designs already routinely include reserve compressor capacity in the form of a back-up or swing compressor. For demand response, additional suction group capacity is not required beyond the back-up or swing unit.

### **4.2.1.3 Control Considerations**

There are several control-related elements in a refrigerated warehouse that must be considered when assessing feasibility of implementing a demand response strategy in a refrigerated warehouse. This section takes a closer look at the following elements:

- a. Evaporator Fan Speed Control
- b. Compressor Part-Load Efficiency
- c. Defrost Considerations
- d. Space Temperature Variability

#### **4.2.1.3.1 Evaporator Fan Speed**

All electric energy consumed by evaporator coil fans becomes heat load in the refrigerated space, not just the waste heat from fan inefficiency. Therefore, reducing fan energy is both a direct savings and an indirect one, seen as a reduction in compressor energy—for a standard freezer system operating at typical conditions, a watt of fan power reduction would result in approximately 0.3 watts of compressor energy reduction.

In addition, variable-speed evaporator coil fan control provides an option to limit the coil fan speed during demand response events, significantly reducing fan power while also maintaining a baseline level of air circulation and productive cooling in the space. The temperature rise during demand response events may be limited, or possibly even completely mitigated, by allowing the fans to run at reduced speed. The fan speed can also be limited during the period after a demand response event, to prevent all evaporator coil fan speeds from ramping to 100% speed at the same time, which could result in an acute spike in electric demand that may nullify the economic benefit of participating in the demand response event in the first place.

#### **4.2.1.3.2 Compressor Variable-Speed Control**

For screw compressors, variable-speed control (when implemented in conjunction with automatic compressor sequencing) improves the efficiency of the suction group when operating at reduced capacity. For all compressor types, having one variable-speed machine in a suction group allows the group to continuously modulate capacity to match the time-variant suction load, resulting in more stable (and higher) suction pressure control.

Improved part-load suction group efficiency will result in higher demand shed for demand response strategies where the refrigeration system is not completely shut off. For instance:

- If a capacity-limiting strategy is employed where the refrigeration system is kept running during a demand response event, either by reducing the evaporator coil fan speed or selectively shutting off some coils
- For facilities where the refrigeration system serves a mix of long-term warehouse storage space and processing loads, where the process load cannot be curtailed during demand response.

#### **4.2.1.3.3 Defrost Considerations**

Evaporator coil defrosts should be scheduled such that the demand response event period, and the recovery period immediately afterwards, is avoided. Coil defrost periods reduce the refrigeration capacity that is available for space temperature pull-down. Every defrost cycle is a disruption to the cooling capacity in the space. During a defrost cycle, frost does not melt from the coil mass or fins until their surface temperature reaches 32°F. All defrost heat added to the coil mass to raise its temperature from the saturated evaporating temperature to 32°F, plus any additional heat that warms the coil above 32°F after all the frost has melted, must subsequently be removed by the refrigeration system after the defrost period has ended. Once the defrost temperature is attained, more moisture is driven off the evaporator in the form of water vapor. All of this moisture must be re-condensed on the evaporator coil, which requires refrigeration system capacity. If the coil defrosts during the recovery period after a demand response event, the refrigeration system capacity used to recover from defrosting is consequently subtracted from the capacity available to recover the space temperature from demand response.

Evaporator coils in spaces that are maintained above 32°F may partially defrost during demand response events (if partial fan operation is employed for air circulation). In these spaces, the next scheduled defrost following a demand response event is likely to require far less defrost time than a normal defrost, and in some cases might be completely avoidable. Demand defrost technologies are particularly useful in this instance. Freezer spaces are different: the space is below the freezing temperature of water, ice and frost buildup on the coil before demand response will persist on the coil through the duration of the event. It is important for the coils to be mostly defrosted before demand response event starts so that there is adequate capacity after the event for pulldown.

#### **4.2.1.3.4 Space Temperature Variability**

In general, the rate of temperature rise at any given point within a space is mostly uniform throughout the space when refrigeration is turned off, unless a significant source of heat (such as a doorway) is present. Because temperature rise is mostly uniform, it is important for the steady-state temperature in the space to also be uniform.

Good air circulation is essential for achieving uniform steady-state space temperatures. Warehouses where the evaporator coil throw direction is parallel to the pallet racking tend to have better overall air circulation throughout the space, which leads to more uniform space temperature during steady-state operation. Arranging the pallet racks and coils this way also avoids the possibility of stacking pallets in front of the air unit, which shortens air throw distance, disrupts air circulation, and contributes to non-uniform space temperatures.

#### **4.2.1.4 Operations**

There are several operational elements in a refrigerated warehouse that must be considered when assessing feasibility of implementing a demand response strategy in a refrigerated warehouse. This section takes a closer look at the following elements:

- a. System Maintenance
- b. Product Distribution
- c. Training

#### **4.2.1.4.1 System Maintenance**

System maintenance is important to demand response from an efficiency perspective as well as from a system safety and reliability perspective. In the absence of regular equipment maintenance and control strategy review, the energy efficiency and cooling effectiveness of industrial refrigeration systems degrades over time, for a number of reasons, including (but certainly not limited to):

- Set point drift, which erodes system efficiency over time, resulting in higher energy usage and higher energy demand. Some examples of set point drift are:
  - Minimum condensing temperature set points are routinely increased in response to any number of maintenance issues. An operator may notice that an evaporator coil did not defrost completely after a scheduled defrost period, for example, and reactively increases in the minimum SCT control value without further investigation. These types of compensatory adjustments often mask other more critical problems.
  - The saturated suction temperature (SST) set point may be incrementally decreased over time in response to a perceived need for additional evaporator coil capacity (which, ironically, may have the opposite effect, resulting in lowering the set point even more. The result is the creation of an additional suite of problems—lack of suction group capacity, increase in suction group energy usage—while not solving the original issue which may be related to an increase in load or an equipment maintenance issue).
  - If a refrigerated space is not maintaining the space temperature set point, the set point may be incrementally lowered under the false assumption that doing so will somehow increase the refrigeration capacity in the space. The capacity does not increase, and if the influencing element that was preventing the space from meeting the set point is removed or resolved, then the space would become unnecessarily over-cooled, wasting energy and potentially compromising product.
- Bypass of Equipment or Controls. Examples of equipment bypass issues are:
  - Evaporator coil variable-speed drives that are bypassed (e.g. the fan is allowed to run at 100% speed), resulting in high energy usage and demand, and expunging the capability to limit demand during or after demand response events.
  - Compressor sequencing controls that are bypassed or overridden in favor of manual compressor starting and stopping, which may result in several machines operating partly loaded where they are less efficient. Centralized system control is also compromised, requiring more worker effort to participate in demand response events.

- Maintenance issues slowly erode system efficiency over time, increasing electric energy usage and demand. Deferred maintenance also creates safety concerns which are exacerbated when systems are shut down and restarted for demand response events.

Examples of maintenance issues are:

- Fouled heat exchangers
- High levels of scaling built up evaporative condenser tubes
- Clogged filters and strainers
- Damaged infiltration barriers (tattered strip curtains, or malfunctioning or bypassed rollup doors)
- Refrigerant leaks
- Malfunctioning air purgers
- Malfunctioning water treatment systems for evaporative condensers

Performance monitoring can play a vital role in maintaining persistent energy efficiency and identifying systemic problems and maintenance issues in refrigerated warehouses. Performance monitoring can be designed to complement the refrigeration control system(s) at a facility, and additionally provide a platform for continuous improvement and adaptation. Performance monitoring evaluates system data such as equipment status, temperatures, pressures, and power readings to calculate component and system efficiency over time. This type of visibility is necessary to effectively maintain system health and achieve the lowest overall operating cost coupled the highest demand-response readiness.

#### **4.2.1.4.2 Product Distribution**

Product placement within the refrigerated space is an important consideration for demand response. One factor to consider is that pallet racking may place the product in close proximity to the light fixtures. The light fixtures radiate heat onto the product, which may cause the product temperature to rise above tolerable levels if the refrigeration system is turned off. Product placed near doorways or passageways to spaces that are held at a higher temperature may also gain heat from the infiltration. Finally, product placement affects the airflow dynamics within the space. If the product is stacked in front of an evaporator coil, the air conditioned by that evaporator coil is not able to circulate throughout the refrigerated space, which could contribute to regions of warm product. In addition, product that enters the space above the space temperature set point, or product that respire such as produce in produce coolers, should be distributed such that the air is allowed to flow around the product and pull the heat out.

#### **4.2.1.4.3 Training**

Adequate training of system operators can alleviate many of the maintenance issues above, such as set point drift and unnecessarily putting equipment in bypass or manual mode. With a better understanding of why systems are configured the way they are, operators are less likely to make changes without proper notification and consensus from the management team. In addition, training for appropriate facility personnel should accompany any significant change in control strategy, such as when a demand response strategy is implemented. Warehouse

personnel should be aware of when demand response events will occur and what will occur with the refrigeration system when an event happens. Maintenance personnel should understand the processes involved with shutting down and restarting the refrigeration system during demand response. Particularly for plants using ammonia systems, demand response should be designed, implemented and managed within the safety and regulatory requirements that apply to the plant.

## **4.2.2 Practical Considerations**

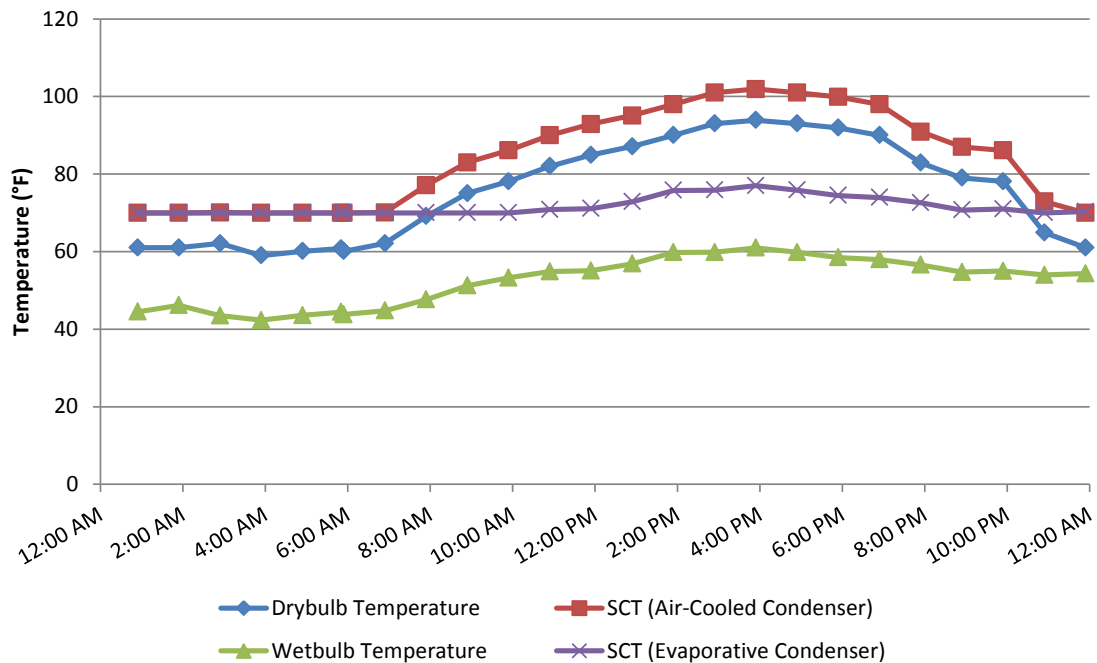
Aside from the considerations related to the refrigerated warehouse facility and operations, there are a number of other considerations related to demand response that are discussed in this section:

- a) Effect of Outdoor Temperatures
- b) Suitability of Controls for Demand Response
- c) Preparing Facility Control Systems for Auto-DR
- d) Safety

### ***4.2.2.1 Effect of Outdoor Temperatures***

Refrigeration systems generally perform more efficiently in cooler ambient temperatures, because the refrigerant saturated condensing temperature (SCT) can be lower (or maintained at the minimum set point for a longer period of time) when the ambient temperature is lower. The difference in night and daytime performance is higher with systems with air-cooled condensers than systems with evaporative-cooled condensers, and consequently, the energy efficiency gain from shifting load from daytime hours to nighttime is more pronounced on systems with air-cooled condensers compared to those with evaporative condensers.

Evaporative condensers respond to the ambient wet bulb temperature, which exhibit much less diurnal temperature variation than the dry bulb temperature that air-cooled condensers respond to, particularly during peak periods. Figure 11 shows the wet bulb, dry bulb, and theoretical condensing temperatures for an air-cooled and evaporative-cooled system over a 24-hour period. Both condensers were assumed to utilize variable-speed fan control with ambient-following condensing temperature set point, and a minimum condensing temperature of 70°F. The ambient-following control TD parameter was assumed to be optimized for both scenarios to deliver the lowest yearly average energy consumption.



**Figure 11: Dry bulb, wet bulb, and condensing temperatures for example air-cooled and evaporative condensers during a sample 24-hour period**

For the example day shown above, the diurnal variation in dry bulb temperature was 35°F, compared to 19°F for the wet bulb temperature. The saturated condensing temperature (SCT) for the air-cooled system reached 102°F SCT, (32°F above the minimum set point), whereas the SCT for the evaporative system only reached 77°F (7°F above minimum set point). The benefit of lower wet bulb temperatures at night, for evaporative condensers, is relatively minor. This, along with the fact that the heat must be rejected during fewer hours of operation during demand response, requires careful control to balance the benefits of demand response and the goals of energy efficiency to achieve the lowest operating cost.

#### **4.2.2.2 Suitability of Controls for Demand Response**

Of primary importance is utilizing controls to ensure safety-of-life, product quality, and regulatory compliance before, during, and after demand response events. An integrated control system is the key to enabling refrigerated warehouses to participate in demand response activities. With the ability to monitor space temperature profiles and to schedule repeatable curtailment responses to grid operator utility requests, facility operators have the ability to fine-tune the demand response strategies for their specific facility and process type. This level of control gives facility managers visibility into the state of their processes at all times, which in turn imparts the confidence to participate in, and try, additional curtailment approaches. Without this level of visibility, the curtailment efforts are likely to be very limited, conservative, or non-existent.

In addition, an integrated control system takes the potential burden of demand response off the shoulders of the operators and facility managers and allows them to continue performing their

job functions. If a facility were manually participating in demand response with a standalone control system for a six-hour event, the activity could take up a significant portion of staff time during an eight or ten hour shift, causing maintenance or repair activities to be deferred. Furthermore, integrated controls eliminate one of the inherent risks of manual demand reduction in a large system, which is the ability (or lack thereof) of the system operators. There can be a wide variation in operator skillsets and how well they understand the nuances of their particular system. Shutting down parts of a complex system can bring up situations not commonly seen during normal operation. Systems with ammonia are especially critical due to the potential hazards in the event of a leak.

While an integrated control system is certainly the most desired starting platform, successfully implementing demand response in a facility with such a system requires additional effort. Most often, additional programming is needed to add demand response capability to the control architecture. The additional programming usually involves developing a demand response master schedule, which would be enabled either manually (manual demand response) or automatically by a utility-sourced signal. This master schedule is used to define the time period of the curtailment. In addition, more programming is then needed to define how each zone or component will respond to this master schedule, based on the facility's curtailment plan. For example, if the facility intends to pre-cool certain zones prior to shutting them off for a few hours in the afternoon, capability would need to be added for the user to be able to define the alternate temperature set point and when the set point should be in effect. Similarly, if the demand reduction plan involves shutting off a significant number of zones in the facility, programming is needed to define when each zone would start pumping down and to stage the zones so there is not too much refrigerant coming back to the engine room at one time. Because the pump down process takes time, the schedules need to be carefully timed in order to ensure the facility has curtailed the desired amount of load by the beginning of the demand response period. Following the event, the re-start of the system(s) must include appropriate time delays to prevent system instability due to the rapid addition of load and to help keep the facility from incurring an excessive demand charge as everything comes back online.

With any changes to a refrigeration control system, documentation of the new control functionality and additional training for the system operators and managers, consistent with plant safety and regulatory requirements, is a must. Because the demand reduction plan may need to be modified occasionally based on current production, weather, or other factors, operators need to be comfortable with adjusting the schedules and staging the curtailed loads.

#### ***4.2.2.3 Preparing Facility Control Systems for Auto-DR***

To dispatch automatic demand response signals, utility companies use centralized DRAS (demand response automation servers). Depending on the program and tariff structure that the facility is enrolled in, the DRAS can dispatch notification signals before events as well as event-start and event-stop signals. Facility operators can also log into their own DRAS accounts to see in real-time how much demand they are using as well as what their real-time load-shed credit is. Refrigeration control systems (and controllers for any other system intended to shed load,



such as lighting) must be made capable of receiving signals from the DRAS. Signals are received and interpreted on-site by devices called OpenADR clients. Clients are configured to interact with the utility's DRAS using OpenADR protocols developed by Lawrence Berkeley National Laboratory. The client is a small electronic device that connects to the DRAS over the internet, and can be configured to enable different digital outputs based on the signals being received from the DRAS. These outputs can be used as inputs to refrigeration control systems to enable schedule-based demand response actions. For example, a day-ahead event notification can be used to enable a zone precooling schedule, an hour-ahead notification signal can enable a zone pump down sequence, and an event-start signal can be used to turn off a portion of the facility's lights. The event-end signal can be used to enable a zone restart schedule, where refrigeration is allowed to come back on sequentially zone by zone until refrigeration has been restored facility-wide.

### **4.3 Safety**

Large industrial refrigerated warehouses often employ custom, built-up systems that use ammonia as the refrigerant. While ammonia offers high energy efficiency and is environmentally superior to halocarbon refrigerants, ammonia is also toxic to humans. Demand response can create unusual operating conditions or place additional stress on refrigeration components, particularly during start-up following a demand response event.

A demand response event cannot be regarded the same way as an unexpected outage such as a power failure, where the system is typically manually re-started, slowly and deliberately, with a heightened level of human supervision and scrutiny. Similarly, because most systems run 24/7, aside from power failures, system shutdowns are typically scheduled and are manually initiated and carefully overseen by maintenance personnel. For reliable, automatic, and safe demand response capability, the refrigeration system must be capable of both shutting down and starting up automatically, without an unusual level of operator supervision. Also, due to the custom, built-up nature of most ammonia systems, the shutdown and startup sequence for each facility is different, and control functional sequences should reflect this.

Extra scrutiny should be given to the shutdown sequence before demand response. The exact details for pumping down and shutting off system components varies with the specific equipment, design and operations of each facility. Typically, the evaporator coil shutdown sequence should not interrupt a hot gas defrost cycle. Ideally the defrost schedule should not include any defrosts that would not have adequate time to continue through completion before a demand response event can be called. The control system could include a lock-out period to prevent defrosts that are demand-initiated or scheduled based on refrigerant liquid on-time.

### **4.4 Section Summary and Conclusions**

In this section, several specific elements within the refrigerated warehouse structure, refrigeration system, and operational practices are described, where building owners and

operators should give special consideration if they intend to implement a demand response or permanent load-shift strategy.

In addition to facility and operations-related elements, safety is also a component of paramount importance to demand response. A demand response strategy, particularly in warehouses with ammonia refrigeration systems, the system must have sufficient level of automatic supervisory control to shut down and start up the system reliably, automatically, and safely.

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## Glossary

**Aggregator** – Energy brokers that act on behalf of a group or groups of customers that mutually participate in a demand response program. They enlist end-users to participate in demand response curtailment and sell the combined load reduction to utilities and grid operators, and consolidate demands from many small users to reach minimum participation levels.

**Auto-DR** – Automatic demand response. Refers to a demand response strategy where a facility's demand response strategy is automatically started and stopped based on signals that are broadcast by the utility, the ISO, or an aggregator over the internet.

**Blackout** - A short- or long-term loss of the electric power to an area.

**Brownout** - An intentional or unintentional drop in voltage in an electrical power supply system. Intentional brownouts may be used for load reduction in an emergency.

**Condenser** – In the context of refrigeration, a device used to condense refrigerant from its gaseous to its liquid state, by removing heat from it.

**Demand Response** – Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.

**Dry-Bulb Temperature** - The temperature of air measured by a thermometer freely exposed to the air but shielded from radiation and moisture. DBT is the temperature that is usually thought of as air temperature, and it is the true thermodynamic temperature.

**Enthalpy** – A state variable, defined as that consists of the internal energy of the system plus the product of pressure and volume of the system.

**Envelope** – Elements related to the structure of a building, mostly in relation to the specific elements across which heat may be transferred. Building elements include interior walls, exterior walls, roof, floor, windows, and doors.

**Evaporator Coil** – In the context of refrigeration, a device used to convert the refrigerant from a liquid state into a gaseous state. The liquid is evaporated, or vaporized, into a gas.

**Head pressure** – In the context of refrigeration, the pressure of the “high side” of the refrigeration system (e.g. the general pressure at the exit of the compressor, inside the condenser, or upstream of the expansion device).

**Hot Gas Defrost** – A method of removing the ice that builds up on the heat exchange surfaces of evaporator coils. Relatively hot refrigerant from the discharge of the compressor is routed to

the evaporator coil, which warms the heat exchange surface above the melting temperature of ice, causing it to melt away from the coil

**Infiltration** - The unintentional or accidental introduction of outside air into a building, or from one space within the building to another (e.g. inter-zonal infiltration), typically through cracks in the building envelope or through use of doors for passage.

**Lift** – the difference between the saturated condensing temperature (e.g. the head pressure, as pressure and temperature are equivalent for saturated fluids) and the saturated evaporating temperature.

**Load Shedding** – A strategy where refrigeration load is avoided altogether. Turning off the lights during a demand response event is an example of a load shedding strategy

**Load Shifting** – A strategy where refrigeration load is shifted to a different time of the day. Pre-cooling the space below the normal space temperature set point in the morning before a demand response event is an example of a load shifting strategy.

**OpenADR** – Open Automatic Demand Response. A research and standards development effort for energy management led by North American research labs and companies. The typical use is to send information and signals to cause electrical power-using devices to be turned off during periods of high demand.

**Permanent Load Shift** – A strategy of permanently shifting refrigeration load from peak periods to off-peak

**Specific Efficiency** - The full-load condenser Total Heat of Rejection (THR) capacity at standardized conditions divided by the fan input electric power (including but not limited to spray pump electric input power for evaporative condensers) at 100 percent rated fan speed.

**Title 24** - The California Energy Code, part 6 of the California Building Standards Code which is title 24 of the California Code of Regulations, also titled The Energy Efficiency Standards for Residential and Nonresidential Buildings. The code mandates minimum energy efficiency requirements for buildings in California.

**Wetbulb Temperature** – the temperature a parcel of air would have if it were cooled to saturation (100% relative humidity) by the evaporation of water into it, with the latent heat being supplied by the parcel.

## **1.4 List of Acronyms**

ADR – Automatic Demand Response

BIP – Base Interruptible Program

CAISO – California Independent System Operator

CBP – Capacity Bidding Program

CFM – Cubic feet per minute

DBP – Demand Bidding Program

DBT – Dry-bulb temperature

EEM – Energy Efficiency Measure

HID – High-Intensity Discharge

HVAC – Heating, ventilation, and air conditioning

ISO – Independent System Operator

LED – Light Emitting Diode

OPR – Owner’s Project Requirements

PAC – Programmable Automation Controller

PLC – Programmable Logic Controller

RTD – Resistance Temperature Detector

SCT – Saturated Condensing Temperature

SET – Saturated Evaporating Temperature

SST – Saturated Suction Temperature

TD – Temperature Difference

TOU – Time-of-use

VFD – Variable Frequency Drive

Vi – Abbreviation for Volume Ratio, as it applies to screw compressors

WBT – Wet-bulb temperature





# Appendix A: Introduction to Energy Efficiency

Industrial refrigeration uses a significant amount of electricity on a year-round basis and operating refrigeration plants efficiently has become increasingly important. Refrigerated warehouse owners and operators can choose to install or retrofit a system by making capital investments in new equipment, and/or by implementing control strategy improvements, to make their operation more efficient and to reduce operating costs.

In this section, the topics of discussion include:

- a) Common energy efficiency measures in refrigerated warehouses
- b) The relation of energy efficiency to demand response

## A.1 Common Energy Efficiency Measures

This section presents several of the most common energy efficiency measures for refrigerated warehouses. All of the presented measures have been shown to be cost-effective and have a history of successful implementation.

Note that there are myriad of ways to improve energy efficiency beyond industry standard practice. The intention of this section is not to define a comprehensive list of energy-efficiency measures, but rather to present an overview of the most common opportunities, which have a proven track record in the industry.

Measures are divided into the following six subcategories:

- 1) System Measures
- 2) Suction Group Measures
- 3) Condenser Measures
- 4) Evaporator Coil Measures
- 5) Envelope Measures
- 6) Efficient Lighting and Lighting Controls

### A.1.1 System Measures

Refrigeration energy efficiency can be improved system-wide by intelligently controlling the way that the various inter-connected components work together. The common system energy efficiency measures discussed in this section are:

- a. Lift reduction measures such as floating head pressure and floating suction pressure
- b. Mechanical subcooling

### A.1.1.1 Lift Reduction

The “lift” of a refrigeration system refers to the difference between the saturated condensing temperature (e.g. the head pressure, as pressure and temperature are equivalent for saturated fluids) and the saturated evaporating temperature. Figure 12 is a pressure-enthalpy diagram showing the vapor-compression refrigeration cycle, with the concept of lift illustrated.

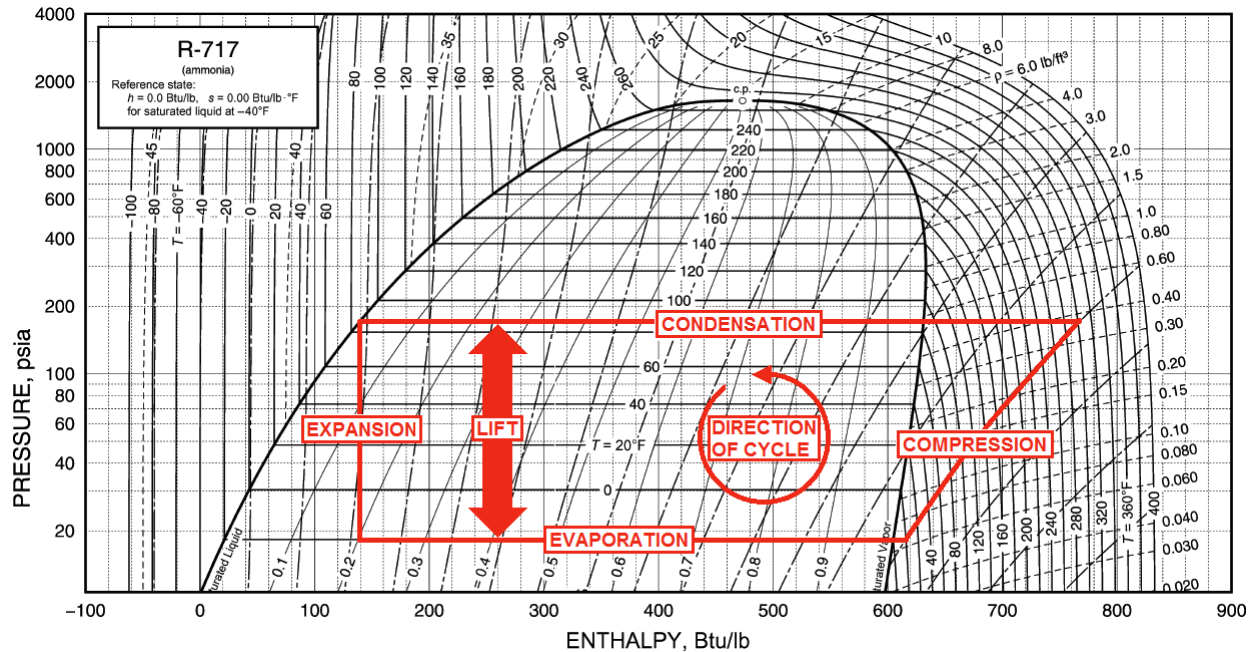


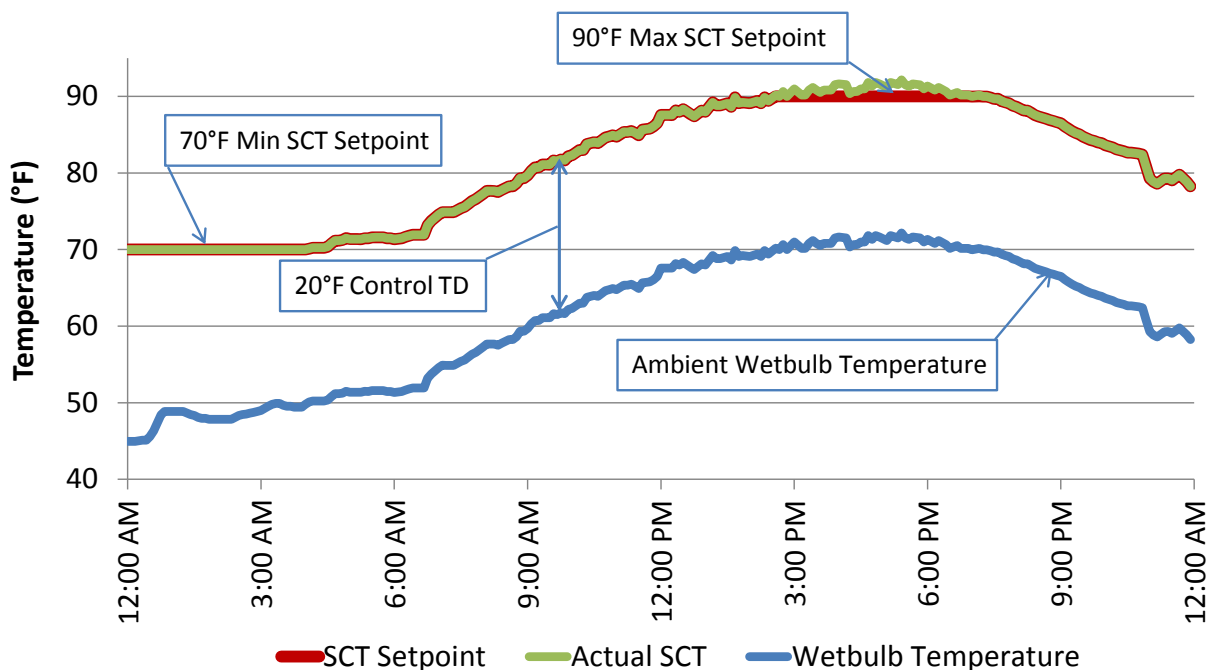
Figure 12: Ammonia pressure-enthalpy diagram, showing concept of lift

Reducing the magnitude of the lift, either by lowering the head pressure or by raising the evaporating temperature, increases the pumping capacity and energy efficiency of the compression stage.

**Floating head pressure** refers to lowering the saturated condensing temperature (SCT), when ambient conditions allow—when ambient conditions are low, the compressor head pressure is also lowered, down to a minimum saturation temperature set point. Refrigerated warehouse systems are routinely able to float to a saturation condensing temperature of  $70^{\circ}\text{F}$  SCT or lower (starting in 2010, California’s Title 24 building energy efficiency standards include a mandate for new refrigerated warehouse systems to float head pressure with a minimum SCT set point of  $70^{\circ}\text{F}$ ).

Current best practice in the implementation of floating head pressure includes ambient-following control logic and condenser fan variable speed control, both of which seek to maximize the energy savings at the refrigeration compressor—optimizing it against the resulting rise in condenser fan energy. The ambient following control logic sets the “target” SCT by adding a fixed control temperature difference (TD) to the ambient temperature (i.e. wet bulb for evaporative-cooled and fluid cooled condensers, or dry bulb for air-cooled condensers). The condenser fan speeds are then continuously modulated to maintain the target SCT. Figure 13

shows the saturated condensing temperature of a refrigeration system with an evaporative condenser, along with the ambient wet bulb, over a 24-hour period. The system depicted in Figure 13 is controlled with an ambient-following (e.g. wet bulb-following) control strategy with a 70°F minimum SCT, 90°F maximum SCT, and a 15°F control TD.



**Figure 13: SCT and wet bulb temperature over 24 hours for a refrigeration system with evaporative condensing**

Variable frequency drives are commonly used to provide continuously variable speed control of condenser fans. Alternatively, controllers designed to vary the speed of electronically-commutated motors (i.e. EC motors, or also known as brushless DC motors) may also be used to obtain variable-speed control of the fans. Current best practice in the implementation of floating head pressure prescribes that all fans serving a common high side, or common cooling water loop for cooling towers or fluid coolers, should be controlled in unison. Therefore, during normal operation at average ambient temperatures, the fan speed of all fans within a single condenser, or set of condensers serving a common high-side, should modulate together rather than running the fans at different speeds or cycling fans off and on. However, when fan speed reaches a minimum practical level (usually no higher than 10-20%), the fans may be staged off to further reduce condenser capacity. As load increases, all fans should be turned back on prior to significantly increasing fan speed, such that an adequate control band is maintained to avoid excessive fan cycling.

**Floating Suction Pressure** refers to reducing the magnitude of the refrigeration compressor lift by raising the saturated suction temperature (SST). Evaporator coils are sized to maintain a design space temperature under design load conditions. Design loads are set high enough to

cover the highest expected load throughout the year, and inherently include safety factors. The actual load on the evaporator coils varies throughout the day, month, and year, and an evaporator coil operating at the design saturated evaporating temperature (SET) has excess capacity at most times. The SET and SST can be safely raised during these times, reducing evaporator capacity and reducing the required lift of the suction group, saving energy at the compressor while also safely maintaining proper space temperature.

In a floating suction pressure control strategy, the target saturated suction temperature (SST) of the suction group is allowed to vary depending on the actual requirements of their associated loads, rather than just fixing the SST set point low enough to satisfy the highest expected yearly load. The target set point is then continuously monitored and adjusted by the control system so that it is just low enough to satisfy the lowest current SET requirement of their associated refrigeration loads while still maintaining (but not exceeding) the target space temperatures. The controls are typically bound by both low and high set points limits which should be established by the system designer. Current best-practice in the implementation of floating suction pressure control strategy includes establishing a minimum value equal to the design SST (i.e. no negative float) together with a positive float range of 4-6°F of saturation pressure equivalent. The latter suction pressure control strategy has been used extensively, obtaining successful results.

#### ***A.1.1.2 Mechanical Sub-Cooling and Flash Cooling***

Liquid refrigerant is said to be subcooled when its temperature is below the refrigerant saturation temperature at a given pressure condition. Sub-cooling requires a heat exchanger to cool the refrigerant at a constant pressure. The same thermodynamic benefit can be obtained by reducing the pressure of the refrigerant and removing the flash gas. Flash cooling is common in large industrial refrigeration systems, with refrigerant “cascaded” from higher to lower pressure vessels. Sub-cooling or flash cooling the refrigerant utilizes cooling capacity from a higher-temperature system (or the economizer port of a low temperature compressor) to cool liquid refrigerant from the condenser before going to the evaporator, which reduces the work of the low temperature compressors. Because it allows some of the productive cooling to be performed at a higher suction pressure, sub-cooling or flash cooling improves overall system efficiency. In addition, sub-cooling can counteract liquid line pressure drop and variations in condensing temperature, facilitating reduced head pressure that in turn increases system capacity and efficiency.

### **A.1.2 Suction Group Measures**

Energy efficiency opportunities can be found at the suction group, either by improving the energy efficiency of individual compressors or by improving the way the group of compressors is controlled. The common suction group energy efficiency measures discussed in this section are:

- a. Energy-efficient compressor electric motors
- b. Screw compressor variable-speed control
- c. Automatic compressor sequencing

### ***A.1.2.1 Energy Efficient Electric Motors***

For open-drive compressor systems, perhaps the most obvious energy efficiency upgrade is replacing the compressor drive motors with high-efficiency units. Industrial refrigeration system compressor motors are very big and powerful, often several hundred horsepower or more. Even small improvements in compressor motor efficiency can significantly impact overall energy savings.

### ***A.1.2.2 Screw Compressor Variable-Speed Control***

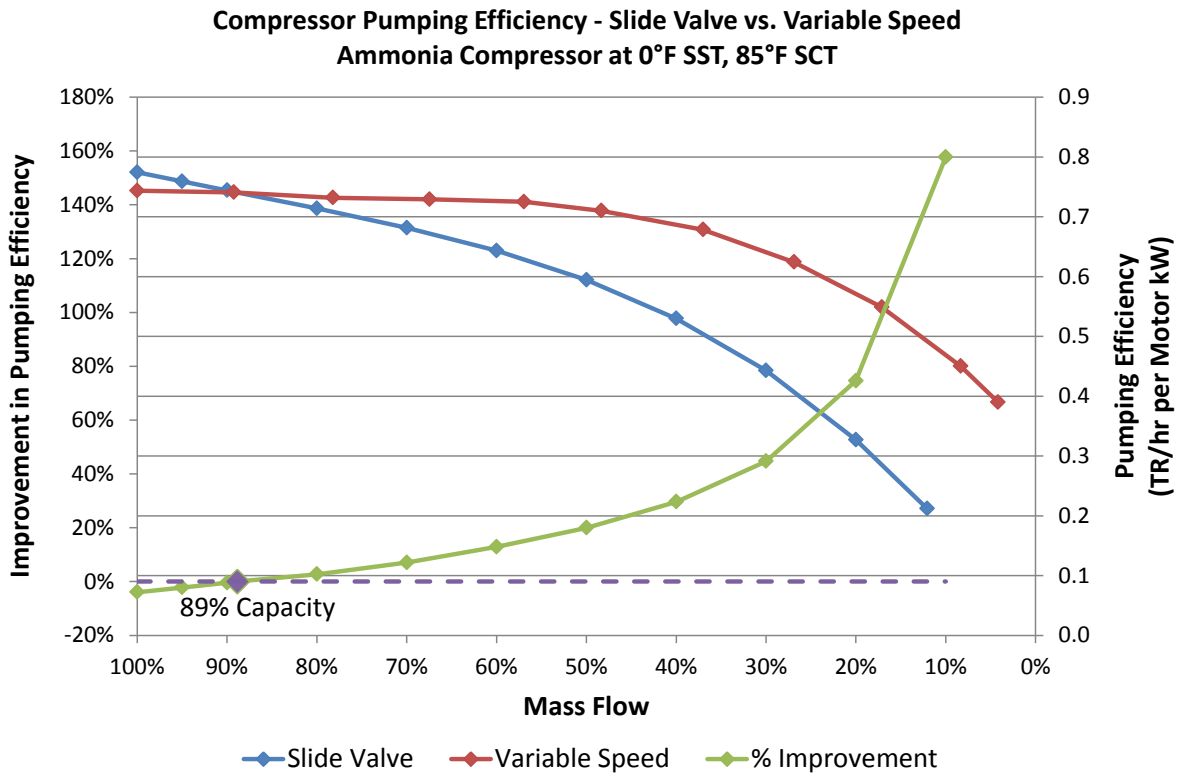
Screw compressors are broadly used in refrigerated warehouse systems. One advantage of screw compressors is that they allow infinitely adjustable capacity control through the use of their integral “slide valve” unloading mechanism. However, this attractive feature does have inherent inefficiencies that substantially reduce energy efficiency when the compressor is part-loaded, namely:

- Loss of efficiency occurs due to friction of the suction gas venting back to the compressor suction inlet via the slide valve
- The slide valve changes the effective compression volume ratio ( $V_i$ ) of the compressor, which is typically assumed to be properly matched to the external design conditions at the 100% capacity slide valve position<sup>3</sup>

Variable-speed motor control via a variable frequency drive (VFD), where motor speed is reduced with the slide valve fixed at the 100% capacity position, presents an attractive alternative to slide valve unloading. Figure 14 shows the improvement in compressor pumping efficiency with variable-speed control compared to just slide valve control. The data account for energy consumed by operating the VFD itself; 2% fixed losses and 2% variable losses are assumed. The slide valve and VFD efficiency plotlines are referenced in the right vertical axis, while the improvement in efficiency of VFD control over slide valve are referenced in the left vertical axis.

---

<sup>3</sup> Most new screw compressors have modified two-piece slide valves that allow the compressor to continuously modulate both the capacity and compression ratio. These “variable- $V_i$ ” machines are quickly becoming industry standard.



**Figure 14: Screw compressor part-load performance with variable-speed control as well as slide valve control**

Figure 14 shows that, due to VFD drive electrical losses, slide valve capacity control is actually slightly more efficient when the unit is near-fully loaded. However, starting at below approximately 89% capacity, the variable-speed unloading strategy becomes more efficient. At lower part-load ratios, the savings are more dramatic: the savings are nearly 20% at 50% capacity for the example machine depicted in Figure 14.

#### ***A.1.2.3 Automatic Compressor Sequencing***

As a general matter of energy efficiency, because industrial compressors are typically designed to be most efficient at 100% capacity, a suction group consisting of multiple compressors should have a compressor designated as “lead”, or “trim” compressor. The trim compressor should handle all of the part-load operation for the entire suction group, while the remaining compressors are either off or operating at (or near) full capacity. Intelligently sequencing the compressors avoids running multiple machines at part-load where they are less efficient. Compressor sequencing typically requires electronic supervisory controls for proper implementation. A common choice is to use programmable logic controllers (PLCs) which are general purpose industrial controls used widely in a many industries.

Only the trim compressor should have a variable-speed drive, and it should be the largest in the suction group (to ensure that there are no gaps in suction group capacity as the non-trim compressors cycle off and on).

### **A.1.3 Condenser Measures**

From the most basic perspective, all heat from the refrigeration system must eventually pass through the condenser. Therefore, it often makes sense to start with improving the condenser when considering energy efficiency enhancements. The common condenser energy efficiency measures discussed in this section are:

- a. Condenser efficiency
- b. Condenser sizing

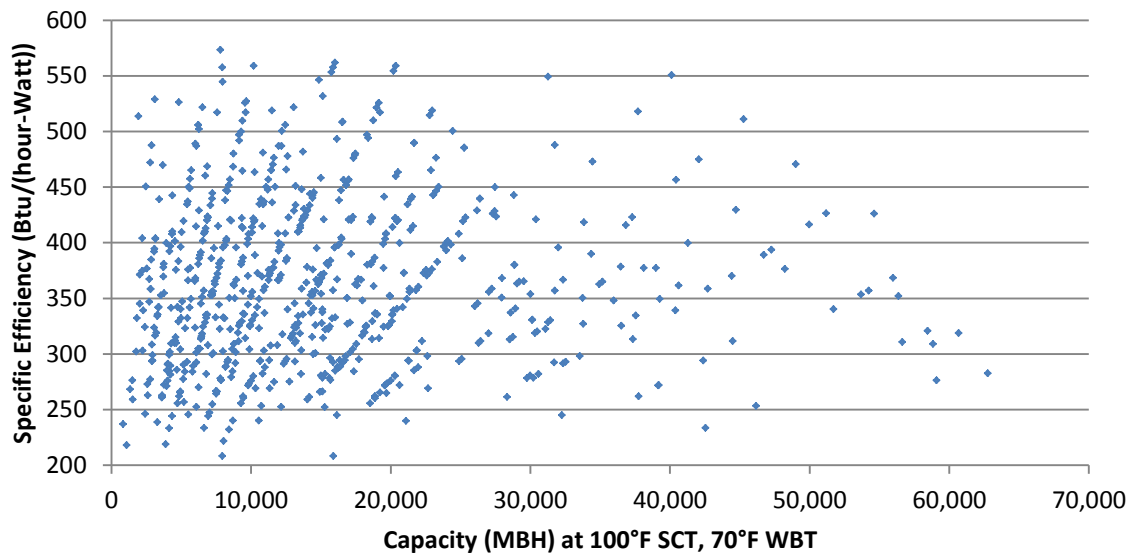
#### ***A.1.3.1 Condenser Efficiency***

The efficiency of a refrigeration system condenser is measured by the unit's heat rejection capacity, divided by the total input electric power. For air-cooled condensers, the input electric power is just for the fan motors, while the spray pump motor is included in the power calculation for evaporative condensers.

Condenser manufacturers offer units in a range of capacities, and for any given capacity there are multiple models of varying efficiency to choose from. Figure 15 shows the variation in condenser specific efficiency<sup>4</sup> across the range of available capacities of evaporative condenser from one major US manufacturer.

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<sup>4</sup> Condenser specific efficiency: an expression of condenser efficiency, in units of (BTU/hour) per Watt. Calculated by dividing the condenser capacity in units of BTU/hour by the condenser input power in units of Watts. For evaporative condensers, the capacity rating condition is 100°F SCT and 70°F WBT. For air-cooled condensers, the rating condition is 10°F TD between SCT and ambient DBT.



**Figure 15: Condenser efficiency versus capacity for all catalogued models from one major manufacturer**

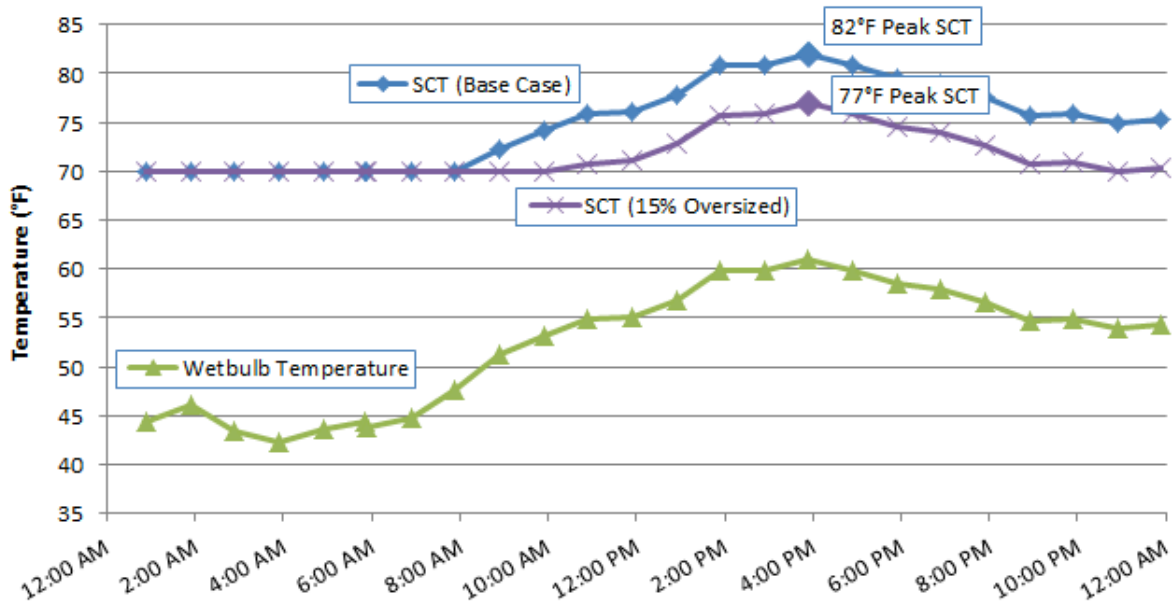
Figure 15 shows the high degree of variation in efficiency across the spectrum of available models. Figure 15 also shows that there is no correlation between efficiency and capacity—for any given capacity requirement, there are a spectrum of available models with broad-ranging efficiencies. Care should always be taken to select the unit that is as efficient as possible, with consideration for other design criteria such as structural limitations, available space, and considerations for fan noise.

#### ***A.1.3.2 Condenser Sizing***

Efficient condensers save energy and reduce peak system demand for every hour that they are operating, and care should obviously be taken to specify condensers that are efficient. Condenser capacity, however, is different than condenser efficiency, and an optimum condenser for demand response is both efficient and also adequately sized.

For a given size of condenser, the condenser capacity is directly related to the temperature difference (TD) between the ambient temperature and the saturated condensing temperature (SCT). For example, a refrigeration system can operate with half the TD if the condenser capacity is twice as large. Figure 16 shows the wet bulb and theoretical condensing temperatures for two different sized condensers over a 24-hour period. Both condensers were assumed to utilize variable-speed fan control with ambient-following condensing temperature set point, and a minimum condensing temperature of 70°F. The ambient-following control TD parameter was assumed to be optimized for both scenarios to deliver the lowest yearly average energy consumption.





**Figure 16: Condensing temperature versus wet bulb temperature for two different-sized condensers**

Figure 16 shows that a larger condenser can maintain the minimum SCT for more hours of the day, and can control the SCT at a lower temperature when the SCT is in the “control range” (between the minimum and maximum SCT). Lowering the SCT reduces the compressor lift, which results in an overall increase in refrigeration system capacity and energy efficiency.

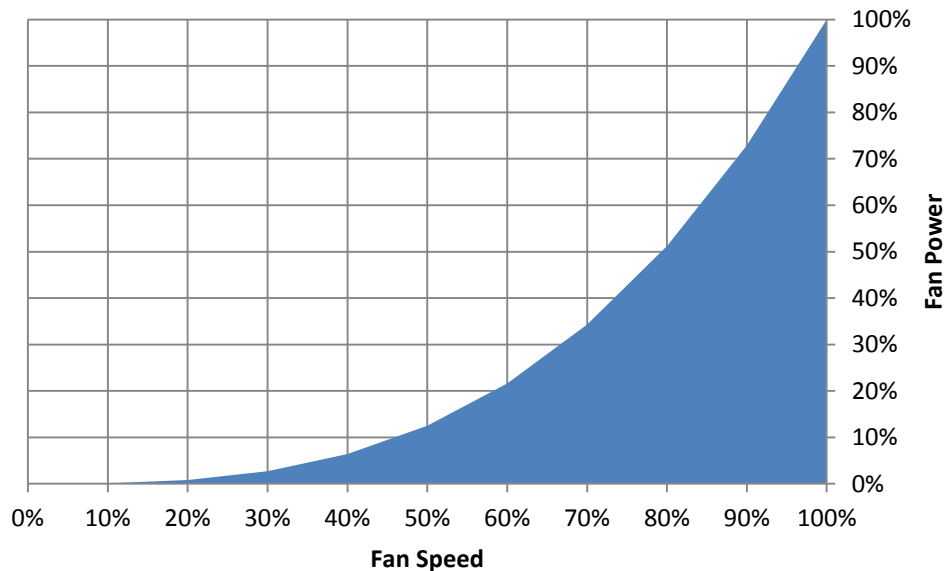
#### **A.1.4 Evaporator Coil Measures**

Several opportunities exist to improve the efficiency of the evaporator coils in a refrigerated warehouse. The common evaporator coil energy efficiency measures discussed in this section are:

- Variable-speed control of evaporator coil fans
- Evaporator coil fan cycling
- Demand defrost and defrost termination

##### **A.1.4.1 Variable-Speed Control of Evaporator Coil Fans**

Variable-speed fan control involves modulating the speed of the evaporator coil fan motors in response to space conditions (typically temperature, but humidity or other factors may also be considered). The measure is typically accomplished by installing a variable-speed drive or by using electronically commutated motors specifically designed to accept a speed-control signal. Variable-speed evaporator coil fan control is beneficial in situations where the refrigeration load in the space is less than the design value for a significant portion of the time, such as in holding coolers and freezers, or where evaporator coil capacity can be “fine-tuned” to match the load from a process, such as blast freezing. For axial fans (such as most evaporator coil fans), the relationship between consumed fan power and fan speed is given by a third-power exponential equation, which is shown in Figure 16.



**Figure 17: Graph of axial fan energy versus speed, showing the “third power” relationship**

Because of the “third-power” fan affinity laws, significant electric energy savings are realized from even modest reductions in speed. For example, based on the affinity laws, at 80% speed, the electric power is just 51%. At 50% speed, the power is just 12%. Actual savings are somewhat less due to inverter losses and other factors. All electric energy consumed by evaporator coil fans becomes heat load in the refrigerated space, not just the waste heat from fan inefficiency. Therefore, reducing fan energy is both a direct savings and an indirect one (seen as a reduction in compressor energy).

#### ***A.1.4.2 Evaporator Coil Fan Cycling***

Fan cycling, or duty-cycling the evaporator coil fans in response to space temperature or other conditions, is an attractive alternative to fan speed control in situations where the potential energy savings may not justify the capital investment of a variable-speed drive, or motor replacement and controls upgrade. Fan cycling reduces the overall run time of the fan motors, providing direct motor energy savings as well as savings from reducing the heat load in the refrigerated spaces.

#### ***A.1.4.3 Demand Defrost and Defrost Termination***

Evaporator coil performance is enhanced with “Demand Defrost” technologies, which initiate an evaporator coil defrost based on frost development (detected by special frost-detection sensors on the evaporator coils), and defrost termination based on coil temperature or frost detection. These technologies are used in lieu of daily defrost scheduling and time-termination.

Demand defrost control saves energy by reducing the average frequency of defrosts throughout the year, compared with fixed scheduled defrost settings which are necessarily set to meet the maximum expected frost load throughout the year, which occurs infrequently. Reducing the number of defrost cycles will increase the overall time that active refrigeration can be on, resulting in an overall increase in energy efficiency in the form of lower evaporator fan speeds

and higher average suction pressure. Reduced defrost quantities also mean less heat introduced into the space, resulting in compressor energy savings. Terminating the defrost cycle based on frost status rather than staying on for a fixed duration will also result in more hours of active refrigeration and an increase in overall system energy efficiency like demand-based defrost initiation.

### **A.1.5 Envelope Measures**

Envelope<sup>5</sup> enhancements reduce the heat flux into the refrigerated space, either by decreasing the conductive heat transfer from the space surfaces, or by reducing the infiltration air (and related convective heat transfer) through doorways into the refrigerated space. The common envelope energy efficiency measures discussed in this section are:

- a. Increased insulation
- b. Infiltration barriers

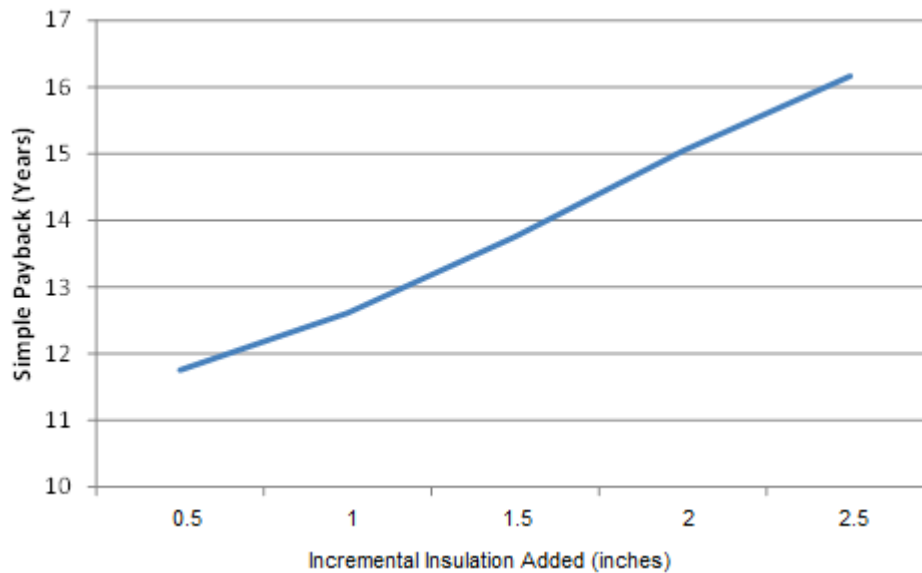
#### **A.1.5.1 Increased Insulation**

By increasing the amount of insulation in the walls, roof, and floor (for freezers) of the refrigerated space, heat flux into the space (and the resulting load on refrigeration equipment) is reduced. Furthermore, the benefit of higher insulation values is maximized when the temperature difference between the refrigerated space and the adjacent space is highest (which, in the case of exterior surfaces, typically occurs during the mid-afternoon, when demand response events are most likely to be called).

While load reduction is always beneficial, envelope designers are cautioned not to adopt a “more is always better” approach to insulation specification. The incremental cost of adding insulation is generally linear, but the incremental benefit of additional units of insulation diminishes with each increment of insulation that is added. Figure 18 shows the simple payback analysis results from incrementally adding insulation in the roof of a large freezer warehouse using polyurethane insulation, as calculated using energy analysis software. The incremental payback is calculated versus a baseline of 4” of insulation.

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<sup>5</sup> Envelope: Elements related to the structure of the warehouse: walls, roof, floor, inter-zonal partitions, doors, dock doors, insulation, etc.



**Figure 18: Simple payback versus insulation thickness for a large refrigerated warehouse roof using polyurethane insulation panels**

Based on simple payback, Figure 18 shows that the benefit of incrementally adding insulation diminishes for each successive inch of insulation that is added. The impact of insulation thickness varies by region and climate zone, and is also a function of the space temperature. Engineering study and life-cycle cost analysis should be employed when selecting insulation panels to maximize energy efficiency with acceptable return-on-investment, considering that insulation is effectively permanent for the life of the facility.

#### ***A.1.5.2 Infiltration Barriers***

Infiltration of relatively warmer air into a refrigerated space, either from the outdoors or from an adjacent space controlled to a higher temperature, is a primary contributor to temperature rise in the space. Infiltration is often the cause of inefficiency in boxes that have difficulty maintaining temperature, as it increases both the load and defrost requirements. A strategy for managing infiltration air is therefore considered essential in an overall approach to improving energy efficiency.

Infiltration barrier types include, but are not limited to:

- Simple manual doors
- Strip curtains
- Automatic roll-up or bi-parting doors
- Air curtains

The effectiveness of each barrier type at reducing infiltration varies dramatically. However, infiltration barriers are selected based on a variety of criteria, including opening height (e.g., 14 ft. or higher for fork trucks for high-rise racking) or width, frequency of doorway passages, hours and nature of facility operations, product type vs. suitability of door closures, and other

factors, not just infiltration effectiveness. In practice, infiltration can never be completely eliminated without severe consequences to warehouse productivity. Designers must balance their production requirements with the energy-saving benefits offered by each barrier type.

In general, “passive” barriers, which require no human intervention to close, are better than barriers that require human intervention to close, such as a manual door or a rollup door with a pull-cord closer, which are often simply left open.

### A.1.6 Efficient Lighting and Lighting Controls

All lighting energy in a refrigerated space eventually becomes heat energy, which must be removed by the refrigeration system. Reducing lighting power therefore saves light energy as well as refrigeration system energy—for a standard freezer system operating at typical conditions, a watt of lighting power reduction would result in approximately 0.3 watts of compressor energy reduction.

T-8 and T-5 fluorescent lighting fixtures and LED fixtures have replaced high intensity discharge (HID) light fixtures, such as metal halide and high pressure sodium lamps, in refrigerated spaces. Energy efficiency, in lumens per watt, and heat reduction are the motivating factors. Table 10 compares the properties of high-bay fluorescent lighting to HID fixtures with comparable lighting output.

**Table 10: Fluorescent lighting fixture properties versus high intensity discharge**

FLUORESCENT LIGHTING FIXTURES											
PZT Hi-Bay System	Lamp Qty & Type	Initial Lamp Lumens	Lumen Maint- enance	EOL Lamp Lumens	Total Fixture Lumens	Blist Factor	Fixt Effic- iency	EOL Lumens Per Fixt	S/P Ratio	Net EOL Lumens	Fixt Input Watts
4L-T5HO	4 FP54T5HO	5,000	93%	4,650	18,600	1.00	0.92	17,112	1.62	24,930	234
5L-T5HO	5 FP54T5HO	5,000	93%	4,650	23,250	1.00	0.92	21,390	1.62	31,163	293
6L-T5HO	6 FP54T5HO	5,000	93%	4,650	27,900	1.00	0.92	25,668	1.62	37,395	351
EOL = End of Life S/P Ratio = Scotopic to Photopic Lumens											
Net EOL Lumens = EOL Lumens Per Fixture x (S/P).78 [.78 exponent]											
COMPARABLE HID FIXTURES											
HID Hi-Bay System	Lamp Qty & Type	Initial Lamp Lumens	Lumen Maint- enance	EOL Lamp Lumens	Total Fixture Lumens	Blist Factor	Fixt Effic- iency	EOL Lumens Per Fixt	S/P Ratio	Net EOL Lumens	Fixt Input Watts
MH400	1 Std MH400	38,000	58%	22,040	22,040	1.00	0.75	16,530	1.49	22,561	458
HPS400	1 Std HPS400	50,000	70%	35,000	35,000	1.00	0.75	26,250	0.62	18,080	464

An advantage of fluorescent fixtures vs. HID fixtures is that they have instant-start capability, meaning they can be controlled using motion or occupancy sensors. HID lamps take as much as

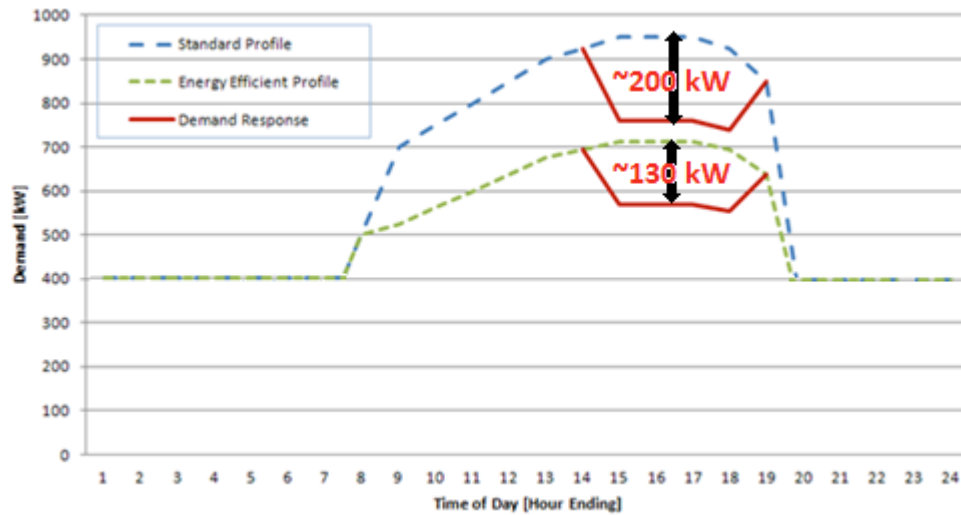
10-15 minutes to warm up before their lighting output reaches maximum levels, and while bi-level HID fixtures are available, power usage is still relatively high even at the lower light level. An important consideration in refrigerated warehouses is that fluorescent fixtures in low temperature spaces typically can only be partially turned off, reducing power by one half or two-thirds, depending on the fixture and ballast design.

LED lighting fixtures suitable for low-temperature applications are relatively new but are rapidly becoming the standard-practice lighting method for California refrigerated warehouses. LEDs offer even higher levels of energy efficiency over fluorescent fixtures. LEDs have instant-start capability, but unlike fluorescent fixtures can be turned completely off, providing greater savings with motion sensors. LED fixtures can also be continuously dimmed, with some vendors providing communicating controllers, allowing fine-tuning of each fixture to optimize performance and savings.

## **A.2 The Relationship of Energy Efficiency to Demand Response**

The prevailing rationale is that energy efficiency measures and strategies should always take precedence over (and form the basis of) an effective Demand Response strategy. Measures that improve the energy efficiency of a facility are said to be effective at all times, while permanent load shifting only affects 600-900 operating hours per year, and Demand Response typically only a few hours per year on declared event days.

In reality, most energy-efficiency measures (or EEMs) typically complement demand response, but the relationship is a delicate one for some EEMs. Many energy efficiency measures are control enhancements that offer more control over the refrigeration system by allowing a component to operate at reduced capacity (where it would previously either just be off or on). Most energy efficiency measures also reduce the peak system demand, which is the stated goal of demand response. Conversely, the magnitude of the demand response potential is reduced when energy efficiency is increased, as shown in Figure 19.



**Figure 19: Demand response potential for a standard- and enhanced-efficiency system**

In terms of overall reduction of peak demand, the example in Figure 19 suggests that a comprehensive energy efficiency strategy in addition to demand response capability provides the greatest reduction in peak demand, even though the magnitude of demand response potential is often made smaller by the energy efficiency enhancements and controls that lower cooling load and/or improve system efficiency. It is important for facility operators to understand this relationship if an energy-efficiency upgrade is planned, considering that energy efficiency measure costs can be significant, and especially if utility incentives are a factor.

The compatibility of an energy efficiency measure to demand response is determined based on a qualitative assessment of the measure's impact. Below are some of the criteria used to evaluate the compatibility of an energy efficiency measure:

- Before an Event
  - Can the refrigeration system better prepare for a demand response event because of an energy efficiency enhancement?
  - Does the measure inhibit the ability to maintain a uniform refrigerated space temperature, increasing the potential for "hot spots" or regions of warm air when the event starts?
- During an Event
  - Does the measure enhance the ability to safely and reliably shed load during a demand response event or permanent load-shift period?
  - Does the measure reduce the heat flux into the refrigerated space during the demand response event or load-shift period, thus maintaining product integrity and reducing the recovery load?
  - Does the measure provide an opportunity to efficiently operate at part-load, allowing some cooling to be achieved during the period while still efficiently reducing demand?

- After an Event
  - Does the measure enhance the ability to more quickly recover from a DR event?
- Overall Performance
  - Does the measure truly improve the energy efficiency (and reduce demand) of the system at all hours, or just during low-load periods?
  - Are the savings from the measure completely negated if the system cannot operate at minimum capacity when shifted load from a demand response event is handled during off-peak hours?

### **A.3 Summary and Conclusions**

Several proven, cost-effective opportunities to either retrofit a refrigerated warehouse for energy efficiency gains, or to ensure that energy efficiency is an engineered design feature of a new refrigeration system, are presented in this section. These energy efficiency measures improve efficiency either by reducing the required electric energy input for the refrigeration system, by helping to curtail the refrigeration load on the system, or by reducing both the load and required energy input. The next section considers additional considerations related to demand response in refrigerated warehouses, including the relationship of demand response capability to some of the energy efficiency measures presented in this section.



## **APPENDIX B: FIELD STUDY DETAILS**

Field studies were conducted at several different refrigerated warehouses in California, in which air temperature and product surface temperature was measured before, during, and after simulated demand response events. The analysis explored the role played by air temperature, product mass, building mass, and various construction features on the space temperature during steady-state operation, and the temperature rise during demand response events.

The analysis also investigated which warehouse usage characteristics, maintenance circumstances, and design features combined to produce local areas of relatively warm air during steady-state operation, and/or contribute the most to space temperature rise during demand response events. Factors such as air circulation, space geometry, construction vintage, infiltration air volume and management tactics, and evaporator fan speed were analyzed. The effect from these factors, and others, are described in this appendix, which includes the following sections:

- a) Scope
- b) Approach
- c) Methodology
- d) Field Study Results
- e) Conclusions

### **B.1 Scope**

Several of the elements discussed in Section 1.2 were chosen for field study, based primarily on opportunity from the mix of warehouses where operators agreed to participate, as well as feasibility of evaluating the element with the monitoring equipment used. Table 8 shows the elements that were examined in this field study.

### **B.2 Approach**

Case study locations were selected to capture a broad range of characteristics, including shape and size, ceiling height, design temperature, type of product stored, vintage, and condition. For this test, effort was made to select a variety of warehouses that reflect the mix of size, shape, design temperature, vintage, product type, and owner practices of the general population of refrigerated warehouses in the country. However, this should not be considered a comprehensive case study of all different permutations of warehouse characteristics, and all different possible factors that may affect space temperature. The analysis is intended to provide general information, sufficient for building owners to make a more informed judgment about how their particular facility might respond thermodynamically to a demand response event. Patterns that were observed at these locations may not be repeatable at other locations.

**Table 11: Demand response considerations and load-shifting/load-shedding strategies explored during field studies**

Considerations			
Facility	System	Control	Operations
I. Lighting	I. Condenser Sizing	I. Evaporator Fan Speed	I. System Maintenance
II. Infiltration	II. Evaporator Coil Sizing and Selection (air throw)	II. Compressor Part-Load Efficiency	II. Product Distribution
III. Underfloor Heating Systems	III. Overall System Design	III. Defrost Considerations	III. Performance Monitoring
		IV. Space Temperature Variability	

Strategies	
Load Shifting	Load Shedding
I. Precooling	I. Lighting Reduction
II. Capacity Limiting	II. Demand Defrost
III. Battery Charger Load Management	III. Underfloor Heater Control
IV. Defrost Scheduling	IV. Infiltration Reduction Strategies
	V. Turning Off Miscellaneous Equipment
	VI. Increasing Space Temperature Setpoint

### B.3 Methodology

Twenty wireless temperature sensors were deployed at five different refrigerated warehouse facilities in California. The sensors were placed at varying heights and locations within the space. Some of the sensor locations were selected to create a “grid” array to test for surface and volumetric effects, such as stratification and exterior wall effects. Other sensor locations were selected in order to observe the significance of different features of interest, such as different types of infiltration barriers, proximity to light fixtures, and the role played by evaporator coil throw length, among others.

The sensors recorded local space air temperature before, during, and up to 24 hours after simulated demand response events. For some facilities, local temperature data were also collected during normal (e.g. steady-state) operation to provide a basis of comparison to the performance during the demand response event, and to illustrate the degree to which space temperature varies within the space during normal operation when refrigeration is on. The analysis also integrated historical trend data from the refrigeration control systems, as well as observations about airflow and air circulation from hand-held anemometers and other measuring devices.

Temperature data were collected in one-minute intervals. Simulated demand response events were variable in duration, but all occurred between 11:00 AM and 5:00 PM on different days in August and September 2013, with some effort to conduct test on particularly hot days.

The following describes the instrumentation used in this study, including:

- a. Temperature Sensors
- b. Anemometer and Draft Detector

### B.3.1 Temperature Sensors

The wireless temperature sensors each consist of a 100 Ohm RTD temperature probe, a microprocessor-controlled radio transmitter, and a plastic enclosure. The enclosures had magnets affixed to the back, allowing temporary attachment of the sensor assemblies to metal pallet racks and metal wall panels in the test spaces. The temperature probes communicated wirelessly with an integrated receiver and web server module, which was connected via Ethernet cable to an Advantech PC (no fan) that polled the web server at one-minute intervals and stored the data. Figure 20 and Figure 21 show the wireless temperature probes.



**Figure 20: RTD temperature probe, transmitter, and enclosure.**



**Figure 21: Wireless temperature probe assemblies deployed on a pallet rack during a case study**

The RTD temperature probe has a published accuracy of  $\pm 0.1^{\circ}\text{C}$  at  $0^{\circ}\text{C}$  to  $30^{\circ}\text{C}$ , and  $\pm 0.3^{\circ}\text{C}$  at  $-50^{\circ}\text{C}$  to  $0^{\circ}\text{C}$  ( $\pm 0.18^{\circ}\text{F}$  at  $32^{\circ}\text{F}$  to  $86^{\circ}\text{F}$ , and  $\pm 0.54^{\circ}\text{F}$  at  $-58^{\circ}\text{F}$  to  $32^{\circ}\text{F}$ ). The sensors were field-

calibrated by allowing all twenty sensors to equilibrate in close proximity to one another in an area of uniform temperature, and recording the relative temperature difference. The calculated relative temperature differences were applied to the raw data collected from each refrigerated warehouse.

Magnetized sensor brackets were also constructed which could be temporarily affixed to metal wall panels. The brackets held the temperature sensors approximately 12 inches away from the wall surface, reducing the effect of radiative heat gain from the wall.

### **B.3.2 Anemometer and Draft Detector**

A Dwyer hand-held anemometer and draft detector were used to map the airflow (relative velocity and direction) at various locations within each of the warehouse spaces. The draft detector uses a non-toxic mixture of water, glycol, and glycerin to generate highly visible smoke, which was used to identify the direction and relative magnitude of airflow, and to identify areas of laminar flow, turbulent flow, swirling, and air stagnation.

## **B.4 Results**

Figure 22 shows the difference between the maximum temperatures recorded at the peak of a simulated demand response event, and the respective space temperature set point during steady-state operation.

Figure 23 shows the maximum, minimum, and average difference between the temperatures at the peak of the demand response event (immediately before refrigeration was restored in the test spaces), and the steady-state temperatures.

The data from each of the six case study test spaces were examined to find elements of particular interest in each of the individual datasets, as well as repetitive trends across two or more test locations. The analysis identified the following four elements as disruptors in refrigerated space temperature:

- a. Proximity to Walls
- b. Light Fixture Influences
- c. Effect of Fan Throw on Air Temperature
- d. Infiltration Air

### B.4.1 Proximity to Walls

Temperature sensors were placed in close proximity to the walls and roofs of several of the test spaces. A subtle, yet distinct, correlation between proximity to the wall and temperature rise during demand response was found at Case Study #3 in particular. Temperature sensors were placed at varying heights and lateral positions next to an inter-zonal wall between the test space and an adjacent produce cooler with a comparable space temperature set point as the test space. Figure 24 shows the difference between the observed peak and the steady-state temperature near the inter-zonal wall, in the aisle, and near the air curtains in the test space.

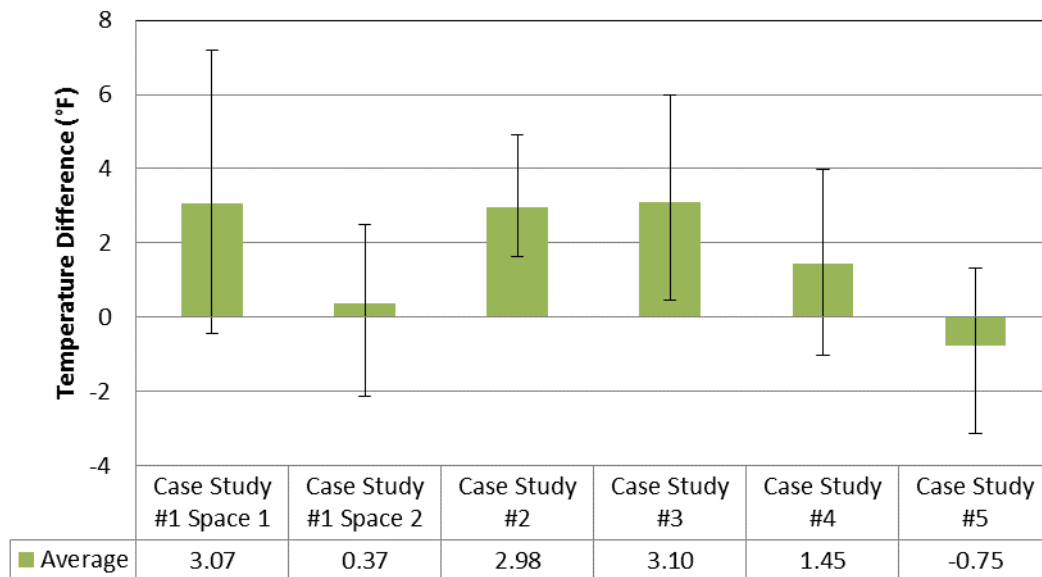
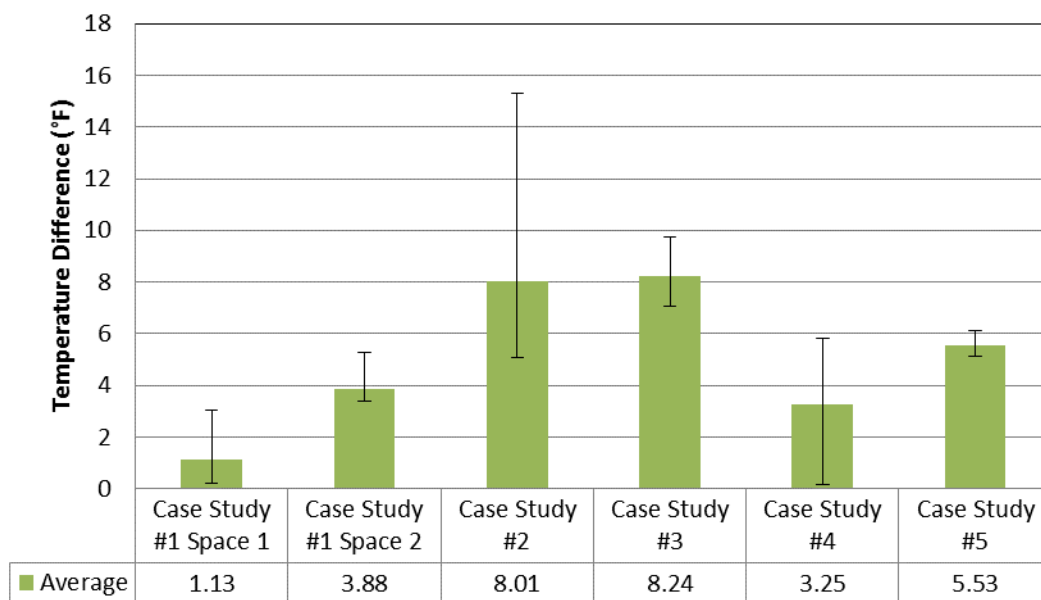
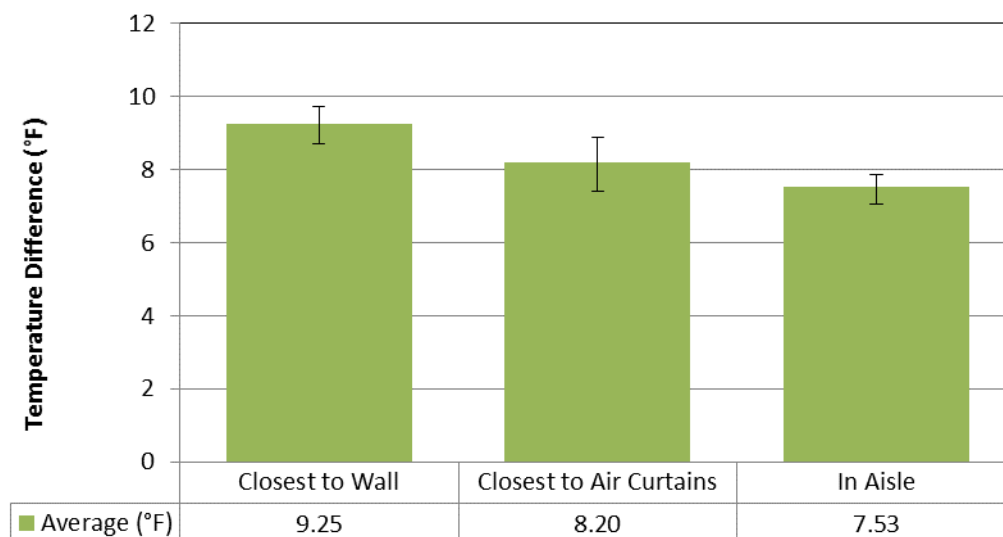


Figure 22: Space temperature difference above set point during normal operation



**Figure 23: Relative space temperature rise during demand response event**



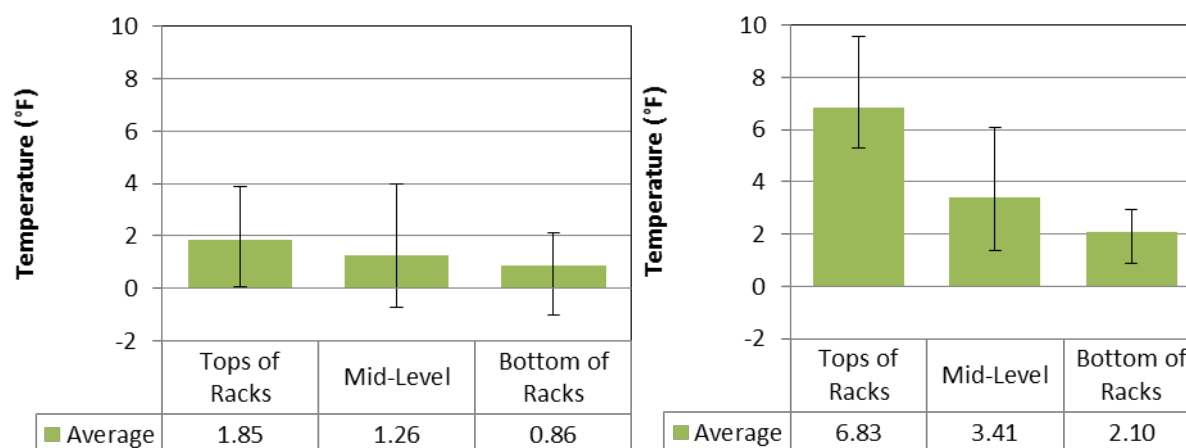
**Figure 24: Difference between observed peak and steady-state temperature at Case Study #3**

Figure 22 shows that the temperature rise was relatively consistent throughout the space—the variation between the maximum and minimum observed temperature rise seen by any two sensors was less than 3°F. However, the data did show a very strong correlation between proximity to the walls and relative temperature rise—the lowest temperature rise at any location near the inter-zonal wall is higher than the highest observed temperature rise of any other location. This contrasts with steady-state data, which showed that the difference between the recorded temperature and the space temperature set point next to walls was not significantly different than at other points. The reason for the trend is not immediately evident:

proximity to walls (even exterior, south-facing walls) was not a significant contributing factor to temperature rise during demand response events at the other Case Studies. The test space at Case Study #3 has metal panel wall surfaces, where other test spaces have plaster, wood, and fiberglass-reinforced plastic (FRP board) wall finishes where wall effects were tested; radiation from the wall surface may be a driving factor.

## B.4.2 Light Fixture Influences

The pallet racking in the test space at Case Study #4 nearly reaches the ceiling, putting stored product in close proximity to the light fixtures. The lighting power in this space is also the highest of all the test spaces, at 0.8 watts of lighting power per square foot of space area.<sup>6</sup> The temperature at the top of the racks was compared to the temperature at the bottom and near the middle of the racks to see if the lights disproportionately affected the air temperature at the top. Figure 25 shows the difference between observed temperature and the space temperature set point for locations at the top, mid-level, and bottom of the pallet racks throughout the test space. The graph on the left shows the average temperature difference during steady-state operation, while the graph on the right shows the temperature difference during the peak of the demand response event (immediately before refrigeration is turned on).



**Figure 25: Case Study #4 space temperature at steady state (left) and during demand response event**

Figure 25 shows that the temperature at the top of the pallet racks is approximately one degree higher than at the floor, on average, during steady-state operation, but the difference climbs to over four degrees over the space temperature set point on average at the peak of the demand response event. Buoyancy-driven stratification may be partially contributing the temperature

<sup>6</sup> The lighting fixtures in all the case study test areas are equipped with occupancy sensors, including Case Study #4, which turn off a portion of the light bulbs in each fixture when motion is not detected below the fixture. The power reflected in the lighting power density calculation is the power consumed by 100% of the lights at full power, without consideration of the effect of the occupancy sensors.

difference, but the high lighting power density and close proximity to the lighting fixtures is likely the primary driving factor.

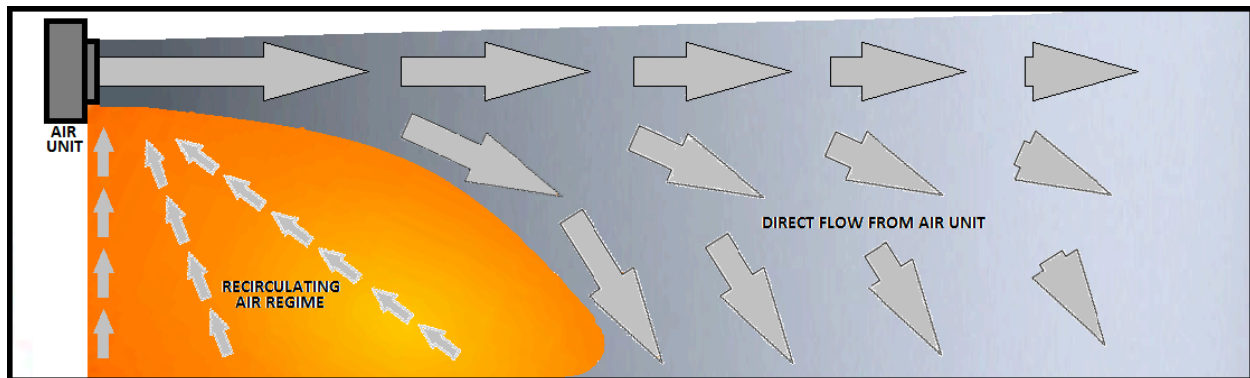
No other case study had pallet racks in such close proximity to the light fixtures.

### **B.4.3 Effect of Fan Throw on Air Temperature**

An airflow pattern was observed in the test spaces at Case Studies #3 and #4, where a regime of slow-moving, laminar, relatively warmer air develops in the area immediately below and downstream of the evaporator coils. Figure 26 shows the location of the observed region.

Both test spaces had similar racking layout and evaporator coil placement, which may be a contributing factor to the development of the observed air regime; evaporator coils were mounted in two rows, each on opposing walls, with pallet racking arranged in parallel with the air throw direction from the coils. The coils on either wall serve alternating aisles, so that the throw for each coil spans the entire length of the test space.

The air in the region of interest is likely pulled from other parts in the space that are outside the path lines of the direct flow from the evaporator coil. The air is not directly conditioned by the evaporator coil, and its temperature has been raised by product respiration, surfaces like the floor and walls, or other heat sources. The air travel within this region is slow and laminar, and is generally toward the discharge of the evaporator coil, not to the inlet of the coil. This is likely due to the effect of entrainment from the discharge airstream.



**Figure 26: Evaporator coil flow regime observed at Locations #1, 3, and 4**

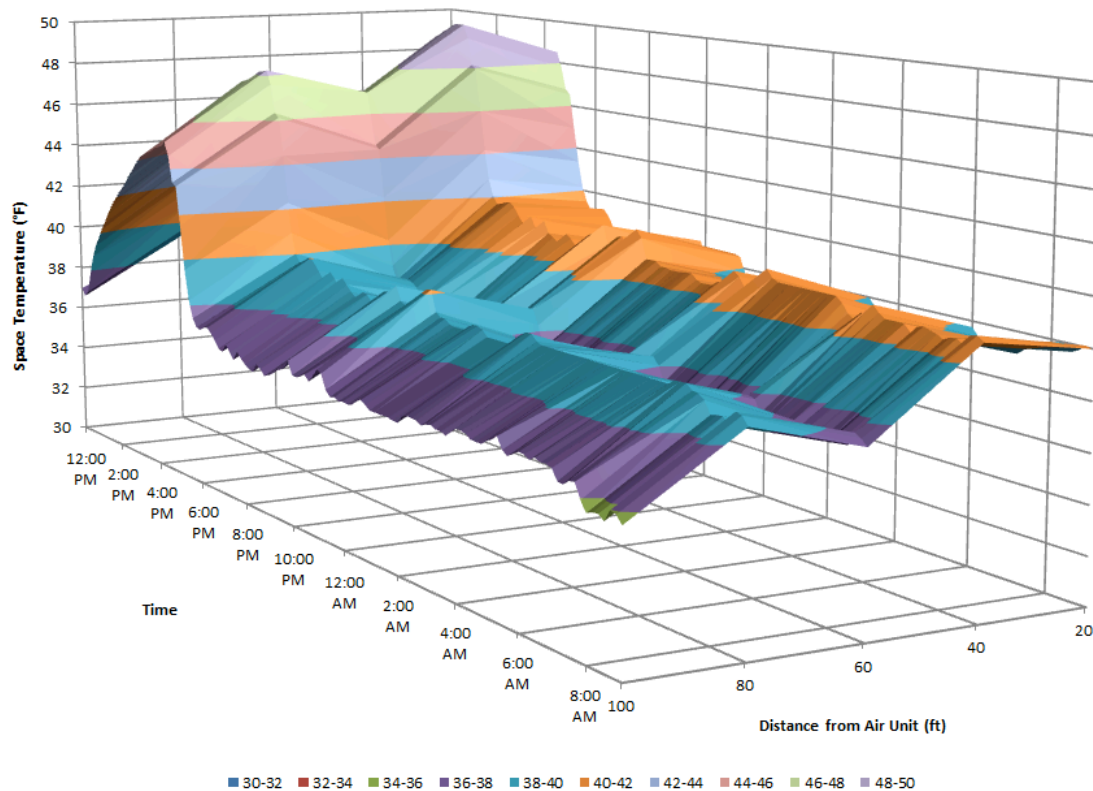
The magnitude of the temperature difference in this region during steady-state operation and during demand response events is presented below for Case Studies #3 and #4.

#### **B.4.3.1 Typical Evaporator Coils**

The evaporator coils in Case Study #3 do not have long-throw adapters, ducting, or other accessories to increase the effective throw length of the evaporator coils. The total throw length for Case Study #3 is approximately 150 feet. Temperature sensors in this area were positioned both at the tops of the pallet racks and at halfway between the floor and the top of the pallet racks, at 20-foot increments starting directly in front of the evaporator coil. Refrigeration in the



test space was shut off at 12:00 PM and restored at 5:00 PM. The temperature profile for this dataset is shown in Figure 27. The figure represents the measured air temperature (vertical axis) versus time (horizontal e.g. bottom left-most axis) and distance from the evaporator coil (depth axis, e.g. the bottom right-most axis).



**Figure 27: Space temperature as a function of distance from evaporator coil during a demand response event for Case Study #3**

Figure 27 shows that during steady-state operation (approximately between 6:00 PM and 8:00 AM) the region 20-40 feet from the evaporator coil is approximately 5°F higher than the space temperature set point, and 5-6°F higher than the region that is over 100 feet from the evaporator coil. At 60 feet from the evaporator coil, the air at the mid-point between the ground and the top of the pallet racks (where the temperature sensors were mounted) transitioned to a regime consisting of cooler, turbulent air flowing directly from the evaporator coil. This is reflected in Figure 27 as a relative valley in recorded temperature, approximately 4°F cooler than the region 20-40 feet in front of the evaporator coil. A second, smaller peak in temperature occurs at 80 feet from the evaporator coil, which is approximately 2°F higher than at 60 feet or at 100 feet. The cause of the second peak is unknown.

During the hours of the demand response event, the relative temperature relationship observed during steady-state operation is maintained, but the absolute temperatures are expectedly higher.

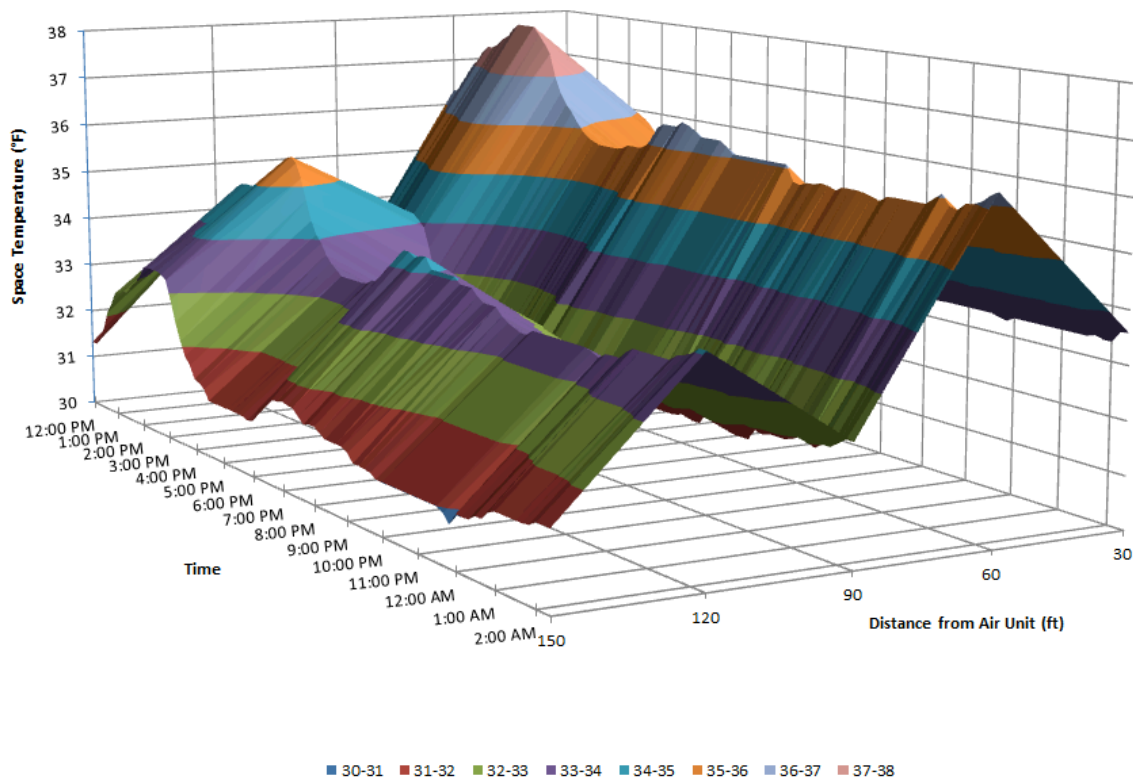
#### B.4.3.2 Long-Throw Fan Adapters

The throw length for the evaporator coils in the test space at Case Study #4 is also approximately 150 feet, but the coils at Case Study #4 have long-throw fan adapters, as seen in Figure 28.



**Figure 28: Long-throw adapters on the evaporator coils in the test space at Location #4**

Temperature sensors in this area were positioned at the tops of the pallet racks, halfway between the floor and the top of the pallet racks, and at the bottom of the racks near the floor, at 30-foot increments starting directly in front of the evaporator coil. Refrigeration in the test space was shut off at 11:00 AM and restored at 3:00 PM. The temperature profile for this dataset is shown in Figure 29.



**Figure 29: Space temperature as a function of distance from evaporator coil during a demand response event for Location #4. The evaporator coils are equipped with long-throw fan adapters**

During steady-state operation (approximately 5:00 PM to 2:00 AM), Figure 29 shows that the region approximately 60 feet from the evaporator coil is 3 to 4°F warmer than the temperature set point, and also 3 to 4°F warmer than the region located 150 feet from the evaporator coil. At 90 feet, the turbulent airflow regime from the evaporator coils widens to include the bottom- and mid-mounted temperature sensors, which is reflected in the graph as a valley with temperatures 2 to 3°F lower than at 60 feet from the coil. As with Case Study #3, a second smaller peak in temperature is observed at approximately three quarters of the throw distance, which cannot be readily explained.

#### **B.4.4 Effects of Infiltration Air on Space Temperature during DR Events**

The field analysis showed that infiltration air, either from adjacent spaces or outside ambient air, had the highest effect on air temperature in the test spaces, both during steady-state operation and during demand response events. Several different infiltration barriers were used in the case study facilities, including strip curtains, two-door vestibules, high-speed rollup doors, and air curtains.

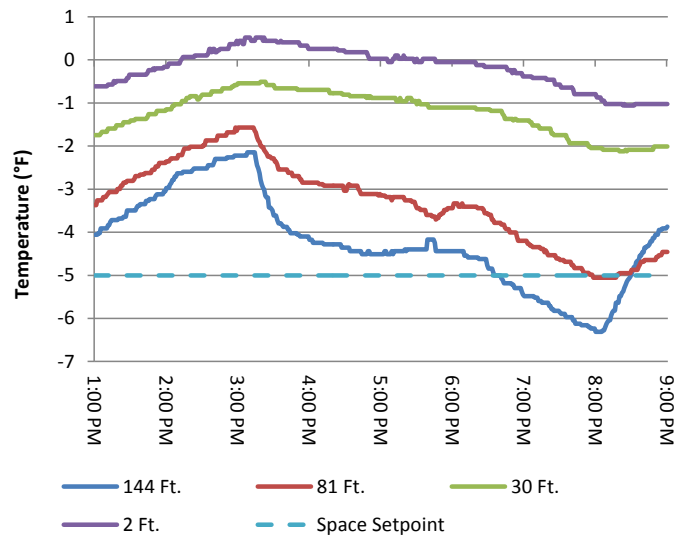
##### ***B.4.4.1 Strip Curtain Vestibule***

The test space in Case Study #1 has a strip curtain vestibule. The adjacent space is a partially conditioned shipping dock. During the test, the evaporator coils in the dock were off, but the temperature was relatively steady around 60°F. The strip curtains on both sides of the vestibules are in good shape. Radiative heaters heated the inside surface of the strip curtains on the freezer side, which created a noticeable difference in air temperature in the freezer near the vestibule. Traffic through the vestibule was moderate during the demand response test, at approximately one forklift passage every 15 minutes. The evaporator coil closest to vestibule in the freezer was inoperable due to maintenance issues during the demand response test. Frost and snow was built up on the wall and roof around the vestibule in the freezer side. Snow would fall in the freezer whenever a forklift would pass through, indicating moderate infiltration from each passage. Figure 30 shows photos of the vestibule.



**Figure 30: Photographs of vestibule at Case Study #1. Clockwise from top-left: view through strip curtain on dock side into vestibule. Heat lamps heating inside surface of strips closest to freezer. View of strips from inside freezer. Notice frost and snow buildup on the wall above the door. Frost and snow on walls and roof above strip curtain entrance.**

Temperature sensors were placed in sets of three on the pallet racks at 2 feet, 30 feet, 81 feet, and 144 feet from the vestibule in the freezer space. At each location, one sensor was placed at approximately 5 feet from the floor, 17 feet from the floor (approximately half the height of the pallet racks), and 28 feet from the floor (at the top of the pallet racks). Figure 31 shows the recorded space temperature versus distance from the vestibule, for the average of each group of sensors.



**Figure 31: Space temperature versus time at varying distances from Location #1 inter-zonal door**

Figure 31 reveals several noteworthy details:

- At the peak of the demand response event, the temperature was as much as 5°F higher than the space temperature set point, on average, two feet from the vestibule. At 144 feet from the vestibule, the temperature rise above the set point is less than 3°F, less than half of the temperature rise next to the vestibule.
- The average rate of recovery is slower near vestibule, where the space temperature recovers to steady-state levels after approximately 4.5 hours. The total pulldown there is approximately 1.5°F, for a recovery rate of approximately 0.3°F per hour. At 144 feet from the vestibule, it takes 1 hour to pull down over 2°F, on average, a recovery rate that is over six times higher than by the vestibule.
- The steady-state (post-recovery) temperature near the vestibule is over four degrees higher than at 144 feet away. The temperature near the vestibule never recovered fully to the space temperature set point.

The combination of infiltration air, reduced circulation due to an inoperable evaporator coil, and the presence of a significant heat source (radiative heaters in the entry vestibule) combined to create a local area of warm air, which heated up further during the demand response event, and took longer to recover to steady-state temperatures after the demand response event. The temperature at approximately 30 feet from the vestibule (and in the throw region of working evaporator coils) and beyond were an average of only 1°F above the space temperature set point, and recovered to steady-state temperatures far quicker.

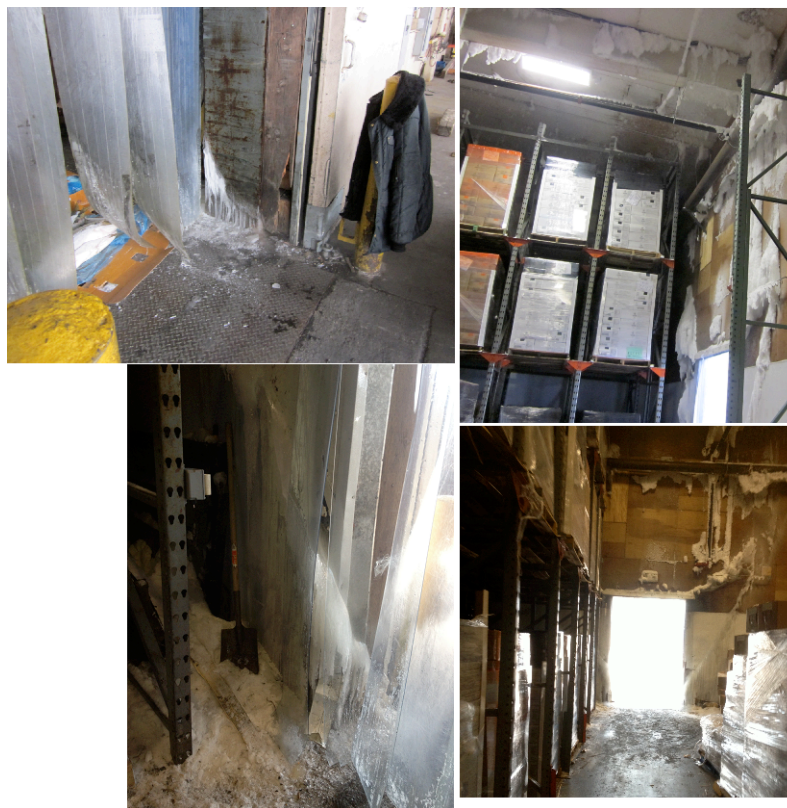
Of the sensors closest to door, the sensors mounted higher on the pallet racks recorded the highest temperatures, suggesting that buoyancy-driven stratification drove the temperature difference. Stratification effects would likely be mitigated if the evaporator coil fans in this area were on.



#### ***B.4.4.2 Strip Curtain Door from Outside***

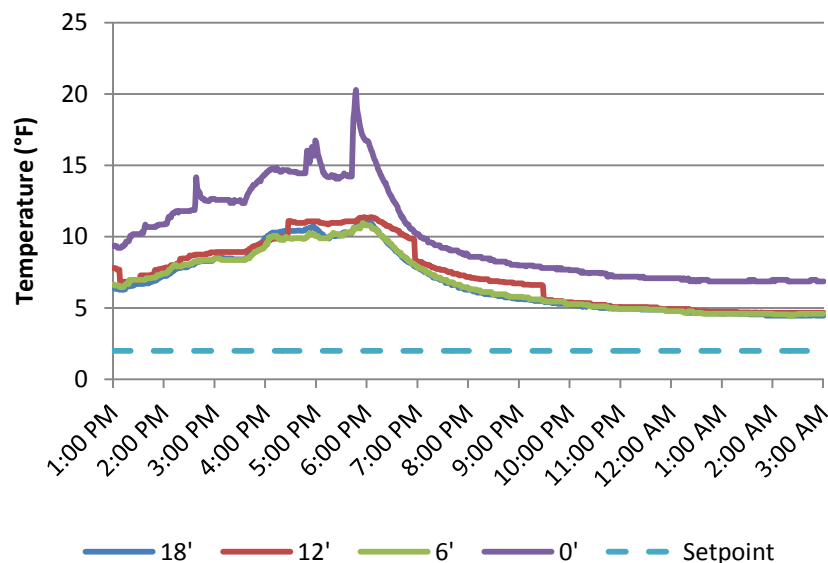
The test space in Case Study #2 has a strip curtain door separating the space from a loading dock area that is completely exposed to the ambient outside air, other than a shading canopy. The strip curtains to the test space were in good shape; none of the individual strips were missing, and there was only light damage to the bottoms of some of the strips. Forklift and worker traffic was heavy during the test, at one forklift passage approximately every two minutes. Inside the freezer, the wall and roof around the door had heavy snow, frost, and icicle buildup, and snow would fall heavily whenever a forklift would pass through, indicating that infiltration load in the space was significant. Over three feet of snow had fallen in the space next to the door, between the pallet racks and the exterior wall.

Sensors were placed in the area that was expected to be “highest risk” to temperature fluctuations during a demand response event, which was both next to door and also the furthest point from the evaporator coils. As noted previously, the pallet racks obstructed the air flow from the evaporator coils, creating several regions of stagnant air within the space. Figure 32 shows photos of strip door.



**Figure 32: Photographs of door passageway at Location #2. Clockwise from top-left: product left in passageway, creating large gaps in strip curtain coverage. Photo of test area where temperature sensors were deployed. View of door, showing snow and frost buildup. 3 to 4 feet of snow near door between pallet racks and exterior wall.**

Temperature sensors were placed at varying heights, from ground level to the tops of the racks, at 0 feet, 6 feet, 12 feet, and 18 feet from the door. Figure 33 shows the temperature profile for the refrigerated space in Case Study #2. A demand response event was simulated at this facility from 1:00 PM to 6:00 PM. The graph shows the average temperature of each sensor group, with distance from the door shown as the independent (horizontal axis) variable.



**Figure 33: Space temperature versus time at varying distances from exterior door at Case Study #2**

Figure 33 shows:

- For sensors between 6 feet and 18 feet away from the door, the temperature rise at the peak of the demand response is over 5°F versus the temperature at steady-state operation, and over 10°F above space temperature set point.
- For sensors closest to the door, the temperature at the peak of the demand response event is over 20°F higher than the space temperature set point and over 13°F higher than the temperature during steady-state operation.
- The rate of temperature pulldown after the demand response event is mostly uniform for each sensor group. Pulldown from peak temperature to within 1°F of steady-state temperature takes approximately 4.5 hours.

The largest steady-state temperature difference above the space temperature set point for any of the test spaces in this study was also recorded at this particular warehouse; the test area was in a corner of the space where circulation was very low and temperature was already very high relative to the other sensors and to the space temperature set point. The combination of high steady-state temperature, plus high levels of direct outside air infiltration resulted in the highest recorded temperature above set point at the peak of a demand response event of any warehouse surveyed in this study.

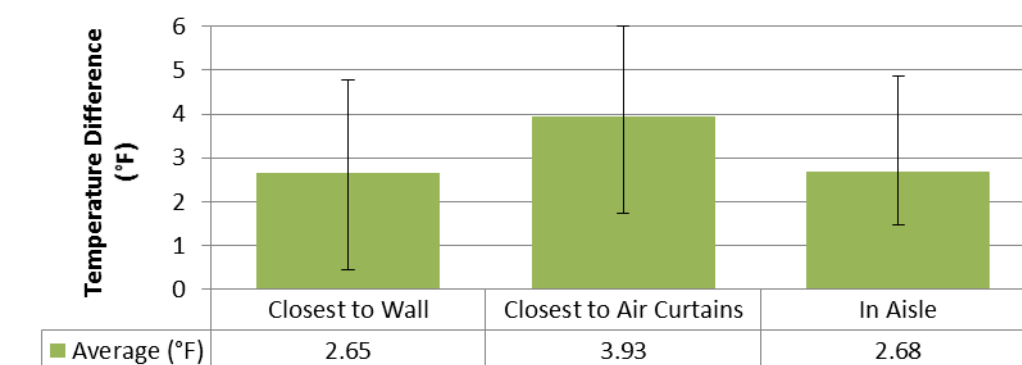
### B.4.4.3 Air Curtains

The test space in Case Study #3 has seven horizontal air curtains separating the test space from an adjacent storage space containing produce and beer kegs, and a vegetable processing area. The temperature set point of the adjacent space is 47°F (15°F higher than the test space), but the evaporator coils in the adjacent space are turned off during business hours to reduce evaporator coil noise and improve worker comfort in the processing area. On the day of the demand response test, the evaporator coils in the adjacent space were off at the start of the test, but were back on when refrigeration was restored in the test space. Air curtain blowers stayed on during the demand response event. The warehouse in Case Study #4 in general has a heavy, continuous flow of forklift and pallet lift traffic, with no exception for the traffic within the test space and passing through the air curtains. Temperature sensors were mostly deployed in the test space, but a sensor array was also deployed in the adjacent space near the air curtains for reference. Figure 34 is a photograph of the air curtains.



**Figure 34: Photograph of air curtains at Case Study #3**

Figure 35 shows the temperature difference above the space temperature set point for the sensors near air curtains, in the aisles between the pallet racks, and near an inter-zonal wall during steady-state operation.



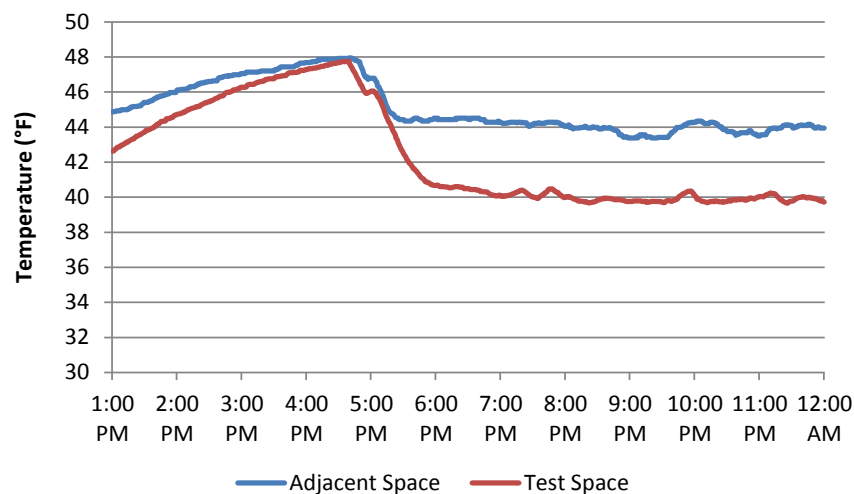
**Figure 35: Temperature profile at Case Study #3**

Figure 35 shows that the temperature difference above the space temperature set point was over 1°F higher, on average, near the air curtains than within the aisles and near the inter-zonal walls



during steady-state operation. While the data suggest that there is a trend of higher temperatures near the air curtains, the average observed temperature variation between the sensors near air curtains and the others is only 1°F.

The situation during demand response, however, was different. Figure 36 shows the average of the space temperature sensors in both spaces versus time for the test space and the adjacent space.



**Figure 36: Average space temperature in test space and adjacent space at Case Study #3**

Figure 36 shows several interesting patterns:

- At the peak of the demand response event, the temperature in close proximity to the air curtains in the adjacent space nearly equals the temperature in the test space. The peak temperature is approximately 48°F, one degree higher than the adjacent space temperature set point.
- The steady-state temperature near the air curtains in the adjacent space is 44°F, which is 3°F cooler than the space temperature set point. The steady-state temperature is also the same as the adjacent space temperature at the beginning of the demand response event.

The fact that the temperature in the adjacent space was 3°F cooler than the space temperature set point at the beginning of the event, even though the air units in the adjacent space were off at the beginning of the test, reveals that the infiltration from the test space into the adjacent space is significant. Furthermore, at the peak of the demand response event, the fact that the test space and the adjacent space temperatures equilibrated suggests that the rate of infiltration is high.

The air curtains stayed on during the simulated demand response event, which matches the strategy employed at the facility for real demand response events. It is important to note that all of the power consumed by the air curtain blower motors becomes heat load, which must be removed by the test space and the adjacent space evaporator coils. With seven air curtains, each

with multiple-horsepower blower motors, the heat load from the air curtains at this warehouse is not insignificant.

The analysis is not intended to discredit the effectiveness of air curtains. Air curtains are selected for a variety of reasons, including the ability to accommodate very high levels of traffic (which, as noted, describes the traffic levels at this facility). However, building operators should account for the relatively low effectiveness of air curtains when formulating their demand response strategy. At this facility, the air curtains separate two spaces whose temperature set points are within 11°F, and the two space temperatures were equal at the peak of the demand response test. If the difference in temperature set point were greater, the temperature rise in both spaces might also equilibrate, resulting in a much higher temperature in the space that has the lower set point.

To improve demand response performance, a better alternative might be to specify air curtains and another form of infiltration barrier, such as a rollup door, for the passageways. The doors could remain open during non-demand response hours, and be closed during demand response events (and during non-business hours). This alternative would provide a more effective infiltration barrier, with only a minor impedance to traffic throughput, during a demand response event when the refrigeration is off. This alternative has the added benefit of providing additional electric demand reduction during DR events, because the air curtain motors could also be turned off.

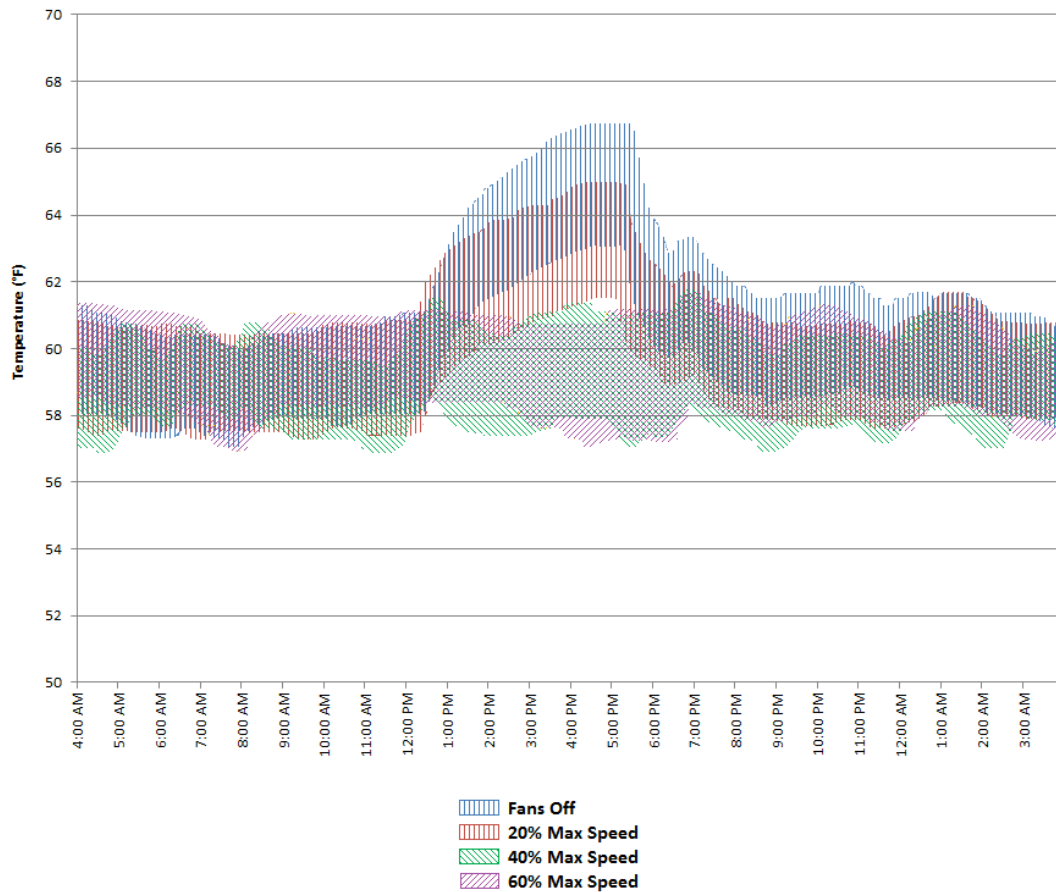
#### **B.4.5 Fan Speed Reduction during Demand Response**

A long-term experiment was conducted at Case Study #5 to determine the effectiveness of reducing evaporator coil fan speed during demand response events. Four demand response events were simulated on four non-consecutive days in August and September. Each demand response event initiated at 12:00 Noon, and terminated at 5:00 PM. For each demand response event, a different maximum fan speed limit was enacted for the evaporator coil fans in the test space:

- Test 1: Fans turned completely off
- Test 2: 20% maximum fan speed
- Test 3: 40% maximum fan speed
- Test 4: 60% maximum fan speed

Groups of temperature sensors were placed at varying heights at 30-foot increments along the path line of the evaporator coil throw direction, with the first group placed immediately in front of the coil and the last approximately 240 feet from the coil, near the opposite wall of the test space.

Figure 37 shows the temperature range for each of the four simulated demand response tests.



**Figure 37: Maximum and minimum measured space temperatures at varying maximum fan speeds during demand response events**

At this warehouse, the space temperature set point was 60°F, which is relatively high compared to typical refrigerated space temperatures. This analysis is intended to show the trend in space temperature at reduced fan speeds; the absolute temperature rise is not the focus of this test, and is likely to be different for other refrigerated spaces, depending on the design space temperature and specific features of the application space.

Figure 37 shows that the temperature rise during demand response was only noticeable when the fans were completely off and when the fan speeds were limited to 20% maximum speed. There was no noticeable change in space temperature when the fan speed was limited to 40% and 60% maximum speed. The figure also shows that temperature span during demand response was the same for all four tests, at approximately 2°F between the maximum and minimum recorded space temperatures at the peak of the demand response events. The span at the peak of the demand response test was also approximately equal to the span during steady-state operation, indicating that space temperature rise during demand response is relatively even throughout the space, congruent with observations from other case studies.

The difference between lowest (near center) and highest (opposite side of space furthest from evaporator coil) recorded temperature value was only 2 to 3°F, on average, indicating that throw length was not an issue in this space, and circulation was adequate on the side opposite the evaporator coil at reduced fan speed to satisfy the load.

## **B.5 Summary and Conclusions**

In this analysis, effort was made to specifically target the areas within each test space where the temperature was expected to be the most affected when refrigeration was shut off during a demand response event. In general, the temperature gains at the peak of the simulated demand response events are likely tolerable for the types of product stored in the Case Study warehouses. With some exceptions (namely direct outside air infiltration into a freezer space), individual influencing features did not typically result in high gains in space temperature. Rather, the highest gains in temperature, where the peak temperature may be deemed too excessive to participate in demand response, were observed where two or more influencing features were present. Examples included:

- Case Study #1, space 1. At this warehouse, the evaporator coil closest to the entry vestibule to the space was down for maintenance. The combination of close proximity to the entry vestibule, a heat source (radiative heating lamps in the vestibule), and low circulation (due to the inoperable evaporator coil) resulted in a temperature of almost 8°F above the space temperature set point during normal (steady-state) operation, and a further gain of 3°F at the peak of the demand response event.
- Case Study #2. Here, the combination of low circulation (a result of pallets stacked directly in front of the coil) and very high levels of unconditioned outside air infiltration resulted in a local space temperature of almost 6°F higher than the space temperature set point during steady-state operation, and a further gain of 15°F at the peak of the demand response event.

This study shows that the largest single contributor to temperature gain during demand response is infiltration air, either from the outdoors or from adjacent spaces that are controlled to a higher temperature. The magnitude of the temperature gain from infiltration varied based on the type of infiltration barrier used, the volume of traffic through the passageway, and the temperature difference between the test space and the adjacent space.

In general, the rate of temperature rise at any given point within a space is mostly uniform throughout the space when refrigeration is turned off, unless a significant source of heat (such as a doorway) is present. Factors such as lighting (and proximity to lighting fixtures), heat gain from interior surfaces—even south-facing, exterior surfaces and roofs—and buoyancy-driven stratification did not significantly affect the space temperature. Note that the analysis revealed that some of these features did locally affect space temperature, but the effect was mostly not significant.

Because temperature rise is mostly uniform throughout the space, it is important for the steady-state temperature in the space to also be uniform. Good air circulation coincided with even steady-state temperatures. The second test space at Case Study #1 had the lowest average deviation (0.4°F), and second lowest maximum deviation (2.5°F) from space temperature set point of any of the case studies. The largest recorded difference in any two sensors was also the lowest at Case Study #2 than at any other test space, at approximately 4.6°F. No discernable correlations could be found between temperature and height, or proximity to walls, roof, or lighting fixtures at this space. Air circulation in this space was very good, with consistent air movement at all tested locations.

As a general observation, warehouses where the evaporator coil throw direction is parallel to the pallet racking tended to have better overall air circulation throughout the space, which led to more uniform space temperature during steady-state operation. In all of the warehouses that had this configuration, the air units and pallet racks were arranged such that each aisle between the pallet racks was served by at least one air unit. Arranging the pallet racks and coils this way also avoids the possibility of stacking pallets in front of the air unit, which was found to shorten throw length, disrupt air circulation, and contribute to non-uniform space temperatures.

Variable-speed evaporator coil fan control provides an option to limit the coil fan speed during demand response events, significantly reducing fan power while also maintaining a baseline level of air circulation and productive cooling in the space. The temperature rise during demand response events may be limited, or possibly even completely mitigated, by allowing the fans to run at reduced speed. Some building designers hesitate to implement variable-speed fan control in refrigerated spaces, because they believe that air circulation will be inadequate at reduced speed to prevent the formation of localized areas of warm air. For this test, no local hot spots were found when fan speeds were limited, even in the areas furthest from the evaporator coil. The test affirms the validity of variable-speed evaporator coil fan control as an energy efficiency measure, and shows how variable-speed can create strategic options for building operators who are constructing a demand-response strategy.

## **APPENDIX C: ENERGY MODEL ANALYSIS DETAILS**

Hourly simulations were utilized for two field study locations to further investigate demand response elements and considerations that the field study could not capture.

### **C.1 Scope**

The elements that are explored in this appendix were primarily chosen for analysis because they could not be evaluated via field study, including:

- a) Permanent Load Shifting and Demand Response on Consecutive Days
- b) Precooling Analysis
- c) Effect of Building and Product Mass

### **C.2 Approach**

Whole-building energy models were constructed to evaluate the energy and cost impacts of both demand response and permanent load-shift control strategies.

The modeling software used for this analysis is DOE-2.2R. DOE-2.2 is a sophisticated component-based energy simulation program that can accurately model building envelope, lighting systems, HVAC systems, and refrigeration systems. The 2.2R version is specifically designed to include refrigeration systems, using refrigerant properties, mass flow, and component models to model refrigeration system operation and controls system effects.

### **C.3 Methodology**

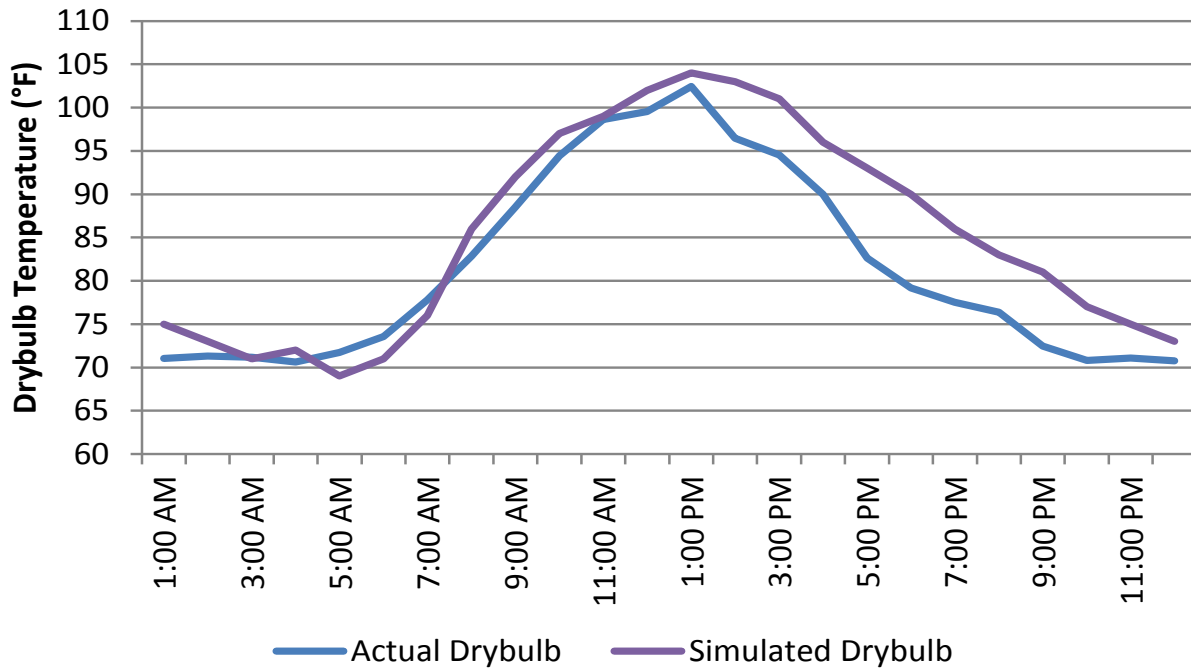
The two energy models are based on Test Space #1 and Test Space #2 at the refrigerated freezer warehouse in Buena Park, California, that was evaluated in Case Study #1 of the field analysis presented in Appendix B. Modeling information for the two refrigerated spaces is shown in Table 12.

The energy models were calibrated using performance data collected by the refrigeration control system, as well as refrigerated space temperature data collected during field analysis. Modeled performance was adjusted based on one hot-weather day in August, where the outside ambient temperature peaked at over 100°F for both the DOE-2 simulation as well as the actual facility. Figure 38 shows the ambient dry-bulb temperature for the actual and simulated ambient dry-bulb temperatures on the days used to calibrate the DOE-2 energy models.

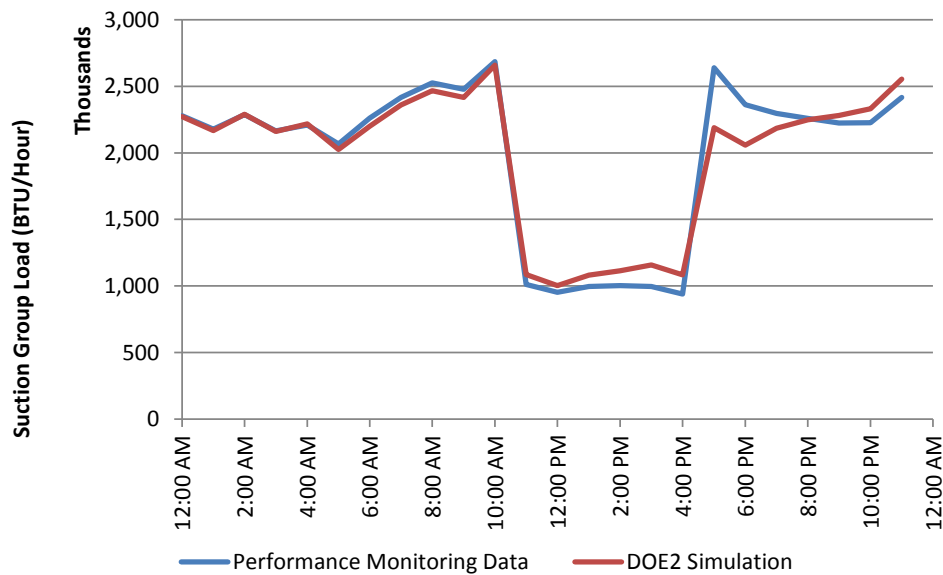
Figure 39 shows the load profile from the actual refrigerated warehouse during a real demand response period, versus the simulated DOE-2 simulated load.

**Table 12: Simulation Assumptions for Energy Analysis**

Test Space	#1	#2
Location:	Buena Park, California	Buena Park, California
Construction Vintage:	1976	2009
Test Space Temperature Set Point (°F):	-5°F	-5°F
Dimensions:	Area: 42,000 SF (226 ft. x 186 ft.) Volume: 1,344,000 ft <sup>3</sup> (32 ft. ceilings)	Area: 26,000 (114 ft. x 225 ft.) Volume: 1,305,250 ft <sup>3</sup> (50 ft. ceilings)
Lighting:	(54) 4-ft, 4-lamp T8 fixtures with occupancy sensors, 0.35 Watts/ft <sup>2</sup>	(68) 4-ft, 6-lamp T5 fixtures with occupancy sensors, 0.85 Watts/ft <sup>2</sup>
Product:	Frozen Seafood	Frozen Seafood
Evaporator coils	(5) 2x10 HP fan coils, 20 MBH ea. @ 10°F TD, variable speed control	(6) 3x3/4 HP fan coils, 14.5 MBH ea. @ 10°F TD, variable speed control



**Figure 38: Actual and simulated ambient drybulb temperatures on the days used to calibrate the DOE2 energy models**



**Figure 39: Load profile for actual system response and DOE2 simulation**

The analysis period is August 1 through August 31, 2013.

## C.4 Analysis

The following topics are explored in this section:

- a) Permanent Load Shifting and Demand Response (DR) on Consecutive Days
- b) The Effect of Precooling
- c) Effect of Building and Product Mass

### C.4.1 Permanent Load Shifting and DR on Consecutive Days

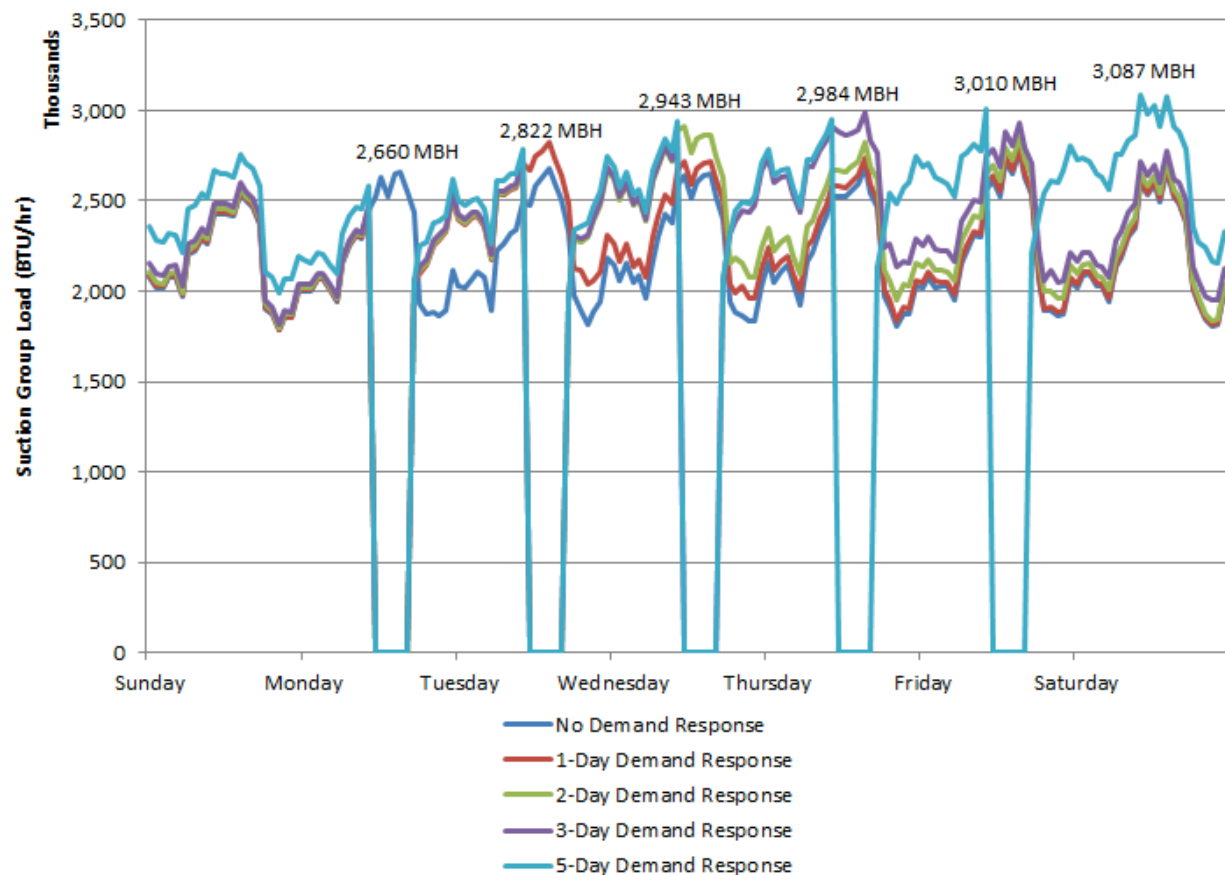
For refrigerated warehouses, demand response events are partially “load-shift” events as well as “load-shed” events. Heat loads that are “shed” (e.g. completely avoided) when the refrigeration system is turned off include evaporator coil fan power (which is usually a significant heat source, given that all consumed evaporator coil fan power eventually transforms to heat load within a refrigerated space—not just the heat from motor inefficiency and friction), and lighting power (assuming lights are dimmed or shut off during demand response). However, the other heat loads in a space cannot be “shut off” during demand response. For example, heat gain from the walls, roof, and floor surfaces cannot be avoided. Usually, loads associated with productivity (infiltration through doors, forklift loads, workers present in the space, equipment in the space such as palletizers or conveyor belts) also cannot be avoided, because production cannot stop during demand response events, which usually occur in the middle of the day. The heat from these sources continues to enter the refrigerated space when the refrigeration system is off, and must be removed during the remaining off-peak operating hours. The refrigeration system is then tasked with removing the heat flux that is



normally present during these off-peak hours, and must also “catch up” on removing the heat that could not be avoided during the demand response event.

If the refrigeration system must “catch up” from one event, while still catching up from an event on the previous day, the sum of the shifted load from both events may exceed the capacity of the evaporator coils or the suction group, resulting in higher space temperatures after sequential event-days.

Consecutive demand response events were simulated in both test spaces simultaneously. Figure 40 shows the refrigeration load served by the suction group that is connected to both test spaces over a one-week period. The chart shows the total load with no demand response events simulated, as well as one, two, three, and five-day consecutive demand response events.

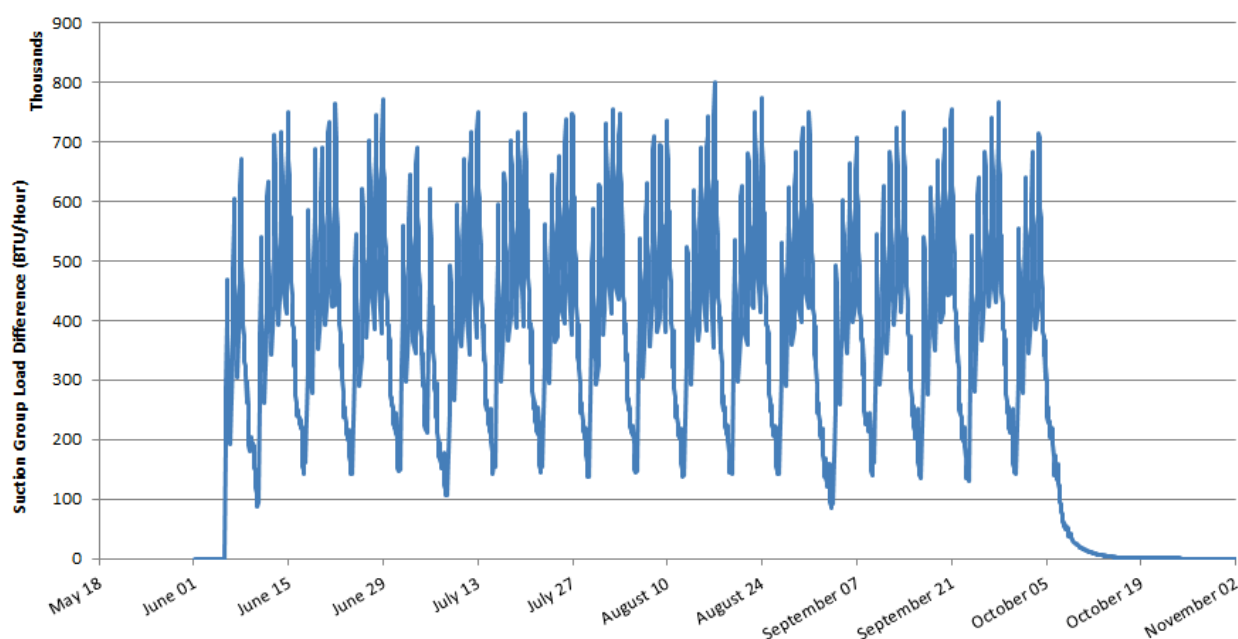


**Figure 40: Suction group load over a 1-week period**

Figure 40 shows the cumulative effect of serially shifting refrigeration capacity on consecutive days. The system load with only one demand response event in the week (the red line), which was simulated on a Monday, is higher than the system load with no demand response events (the blue line) for two days. The two trends eventually equilibrate on Wednesday evening. When two events are simulated on both Monday and Tuesday (the green line), the suction

group requires three additional days to equilibrate. The trend continues for 3-day and 5-day consecutive demand response events.

The figure also shows that the peak daily loads are generally equal for every day of the week when no demand response events are simulated, but are higher on each consecutive day when sequential demand response events are simulated. The graph of the five-day consecutive demand response events shows that the magnitude of the increase in peak daily load is greatest after the first day, and tapers with each consecutive day. The effect on suction group load from implementing a permanent load-shift strategy, where the refrigeration system is shut down every weekday in the summer season, is shown in Figure 41. The graph shows the simulated difference in suction group load between a 5-day-per-week permanent load-shift strategy during the summer season, and a control strategy that does not include demand response.

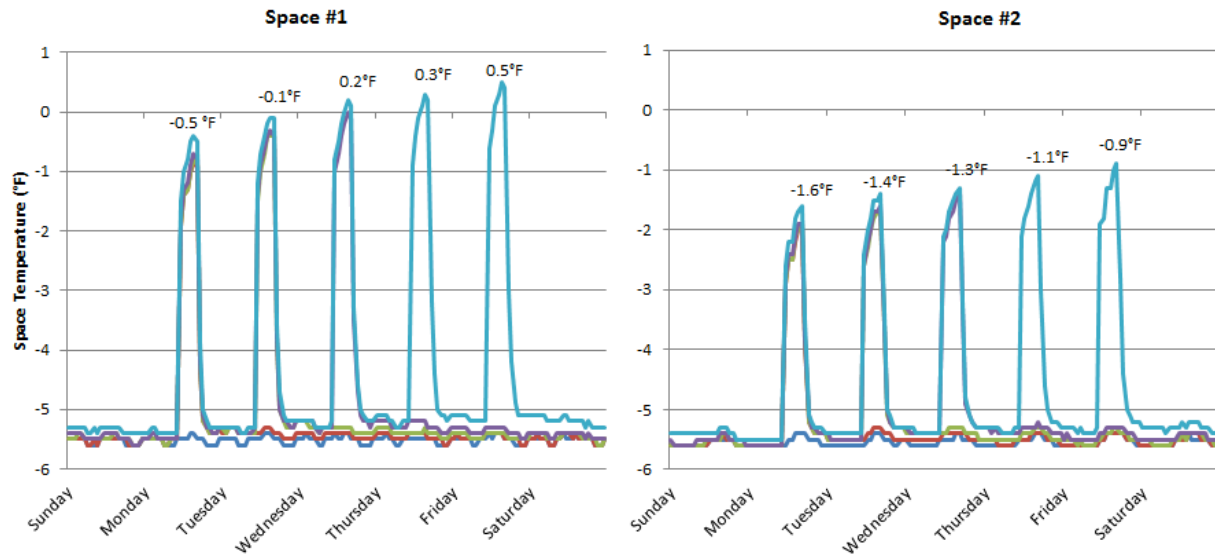


**Figure 41: Difference in suction group load between a 5-day/week permanent load shift strategy and a strategy with no load-shifting, over an entire summer season**

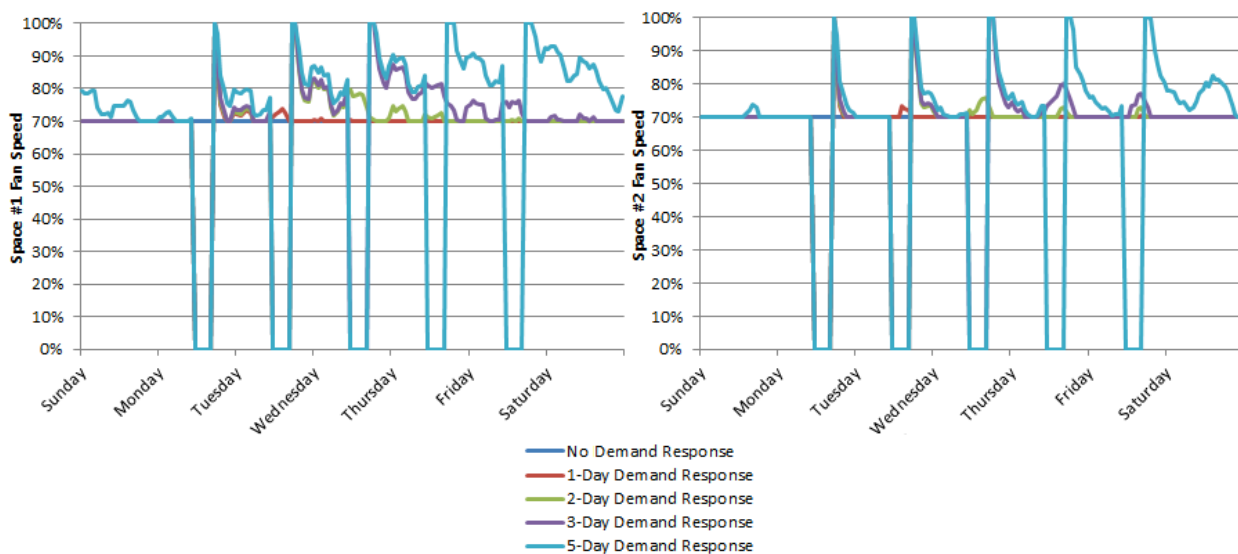
Figure 41 shows that the peak daily load does not increase indefinitely with a permanent load-shift strategy. The under-served load that carries over from day-to-day during the weekdays eventually re-balances with the surplus capacity on the weekend days when the system is allowed to run for 24 hours per day. After approximately two weeks, the system re-balances at a new, higher average weekly load.

#### ***C.4.1.1 Space Temperature and Fan Speed***

Figure 42 shows the simulated space temperature for both test spaces over a one-week period, while Figure 43 shows the evaporator coil fan speed in both test spaces over the same period. The charts show the temperature and fan speed with no demand response events simulated, as well as one, two, three, and five-day consecutive demand response events.



**Figure 42: Space Temperature over one week, with varying numbers of consecutive demand response events**



**Figure 43: Fan speed in Space #1 and Space #2 over one week, with varying numbers of consecutive demand response events**

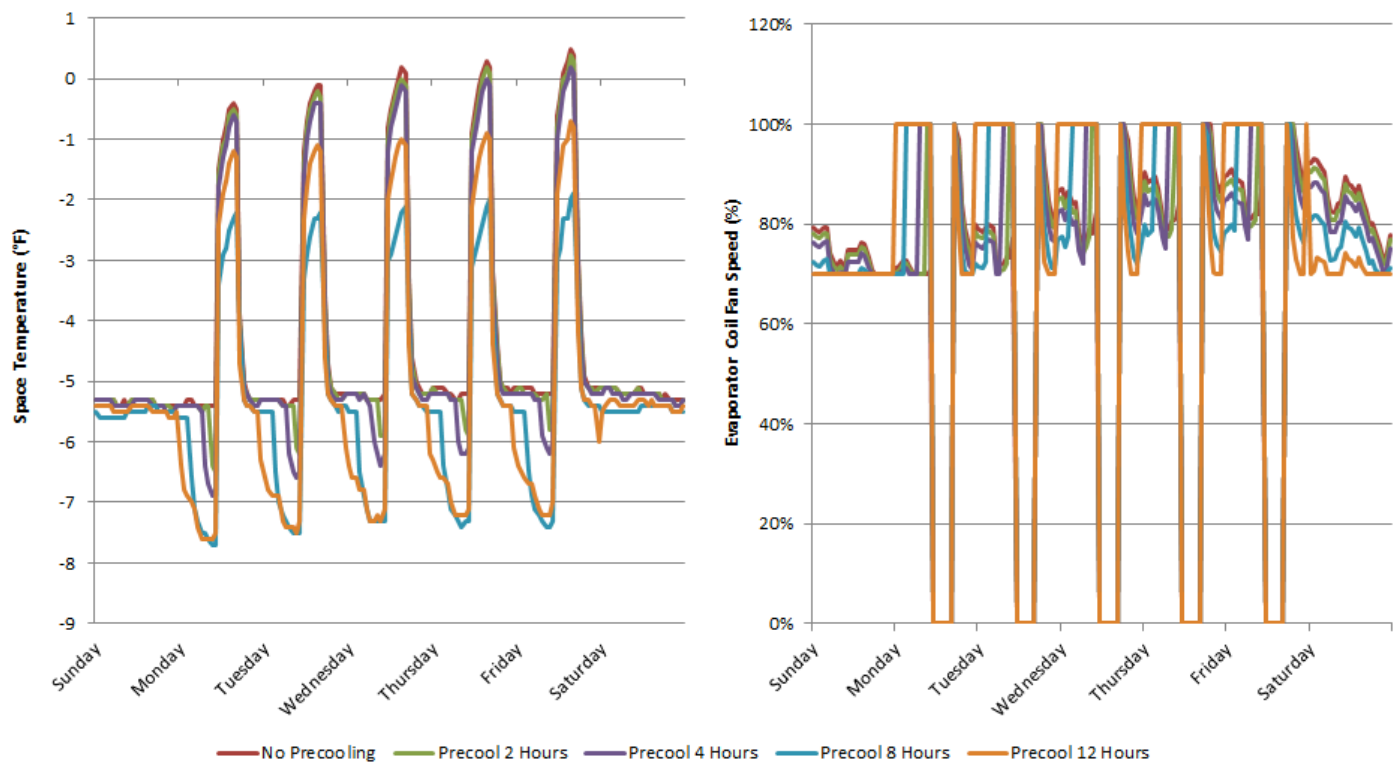
The figures show that the evaporator coil fan speed and space temperature respond as the unserved load in each space accumulates with each consecutive daily demand response event. For both Space #1 and Space #2, fans generally run at the minimum speed (70% in this case) at all hours when no demand response events are simulated. Fan speeds peak at 100% in the hours immediately after a single demand response event is simulated on the first Monday of the week, but return to minimum speed before the evening hours in both test spaces. When consecutive demand response events are simulated, the fan speed remains at 100% for longer, the fan speeds

are higher on average, and the fans takes longer to return to minimum speed after the last event of the week. Figure 42 also shows that the space temperatures at the peaks of the demand response events (immediately before refrigeration is turned back on) steadily increases for each consecutive demand response event.

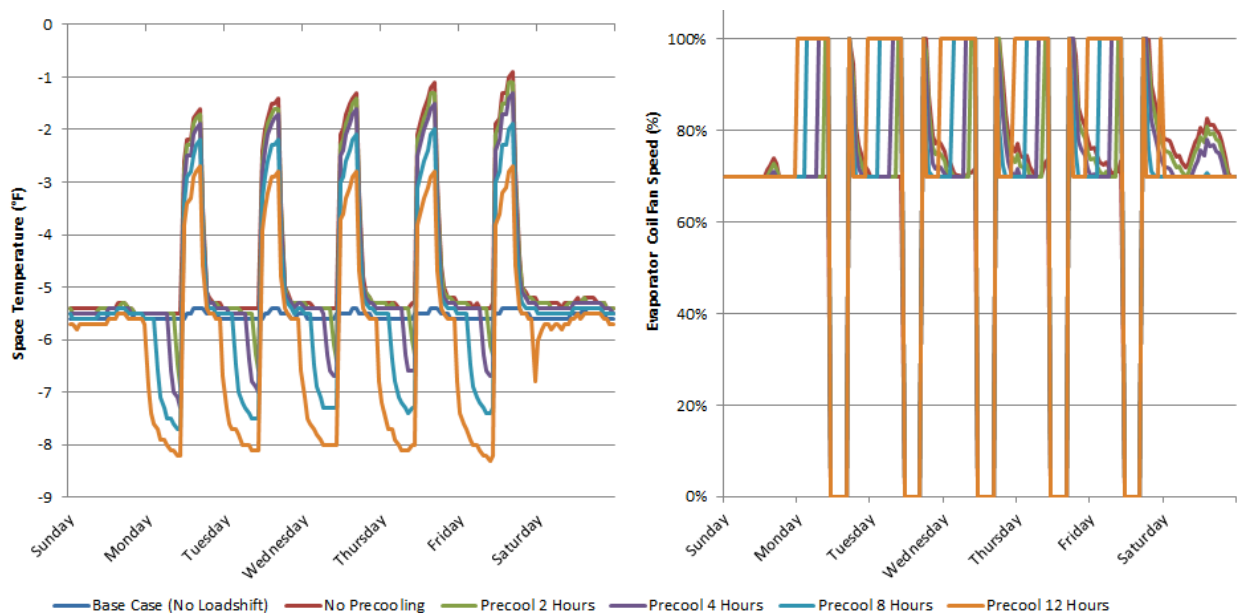
In general, the average fan speed in Space #2 is lower than Space #1 for all simulations. As noted in the Field Analysis section, the temperature rise in Space #2 is lower than Space #1, which is reflected by the lower average evaporator coil fan speeds.

### **C.4.2 Precooling Analysis**

Precooling involves over-cooling a refrigerated space before a demand response event or load-shift period by lowering the space temperature set point for several hours before the event. The figures show the space temperature and fan speed for both simulated test spaces, with varying levels of pre-cooling. Figure 44 depicts Test Space #1 while Figure 45 depicts Test Space #2. In both figures, the models are simulated with a five day per week permanent load-shift strategy.



**Figure 44: Space temperature (left) and fan speed (right) for Test Space #1, with varying levels of space precooling before load-shift periods**



**Figure 45: Space temperature (left) and fan speed (right) for Test Space #2, with varying levels of space precooling before load-shift periods**

The figures show that the maximum space temperature during demand response or load-shift events is significantly curtailed by precooling, but the magnitude of the range in space temperature is generally not affected. The fan speed graphs show that the recovery period after the demand response or load-shift events is inversely proportional to the time spent precooling before the event, but the average fan speed (and the consumed power) is higher with the precooling strategies, because fans are at full-speed during precooling hours.

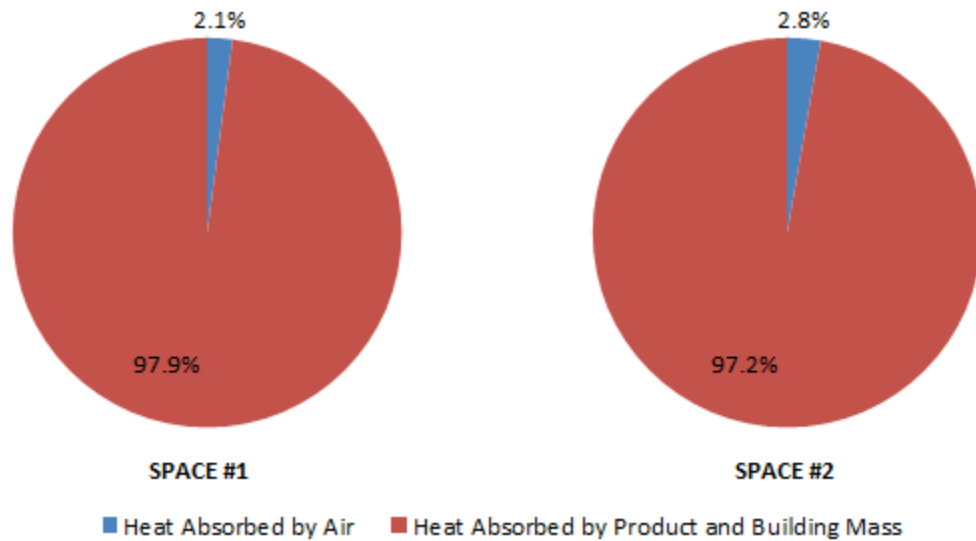
### C.4.3 Effect of Building and Product Mass on Space Temperature

The calibrated refrigeration loads were used to in a calculation to explore the quantity of heat that is absorbed by product and building mass as opposed to the heat that contributes to air temperature rise within the space. Table 13 describes the variables in this calculation.

**Table 13: Variable description for building mass calculation**

<b>Variable</b>	<b>Description</b>
Air mass within the space	Calculated based on space dimensions and air density at space temperature set point
Air temperature rise	Known value, based on sensor data collected during field study, verified with performance monitoring data
Space heat loads	Dis-aggregated loads taken from calibrated energy models. Includes skin loads, product load, people heat gain, heat from lights, and infiltration loads
Heat load absorbed by air	Heat required to raise the temperature of the mass of air in the space by the observed temperature rise during a simulated demand response event. Calculated based on air temperature rise from field studies, calculated air mass in the space, and known thermodynamic properties of air
Heat absorbed by product and building mass	Difference of total space heat load and heat load absorbed by air
Product temperature rise	For one space, calculated based on calculated heat absorbed by product, estimate of product mass in space provided by building operator, and known thermodynamic properties of product

Figure 46 shows the calculated heat absorbed by the air within the refrigerated spaces, versus the calculated heat absorbed by the building and product mass.

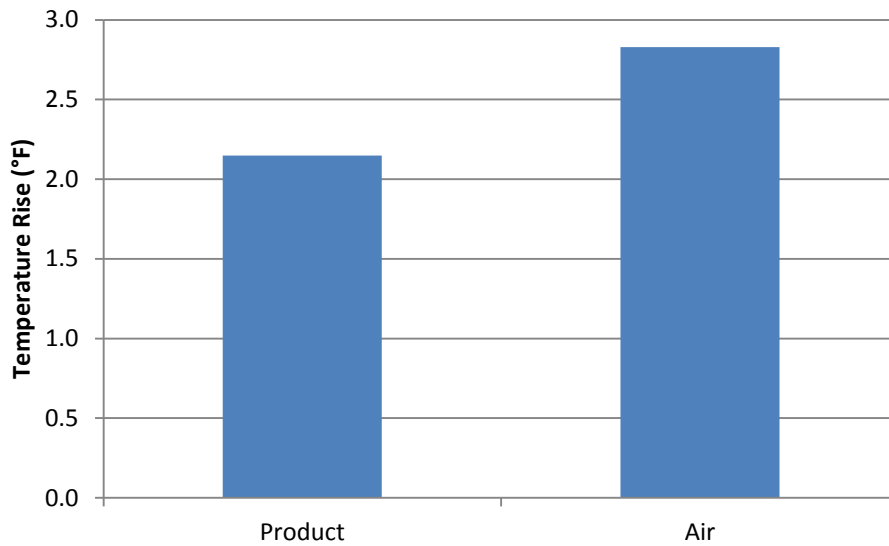


	Space #1	Space #2
Total Heat (BTUs)	5,283,198	3,446,580
Heat into Air (BTUs)	110,865	95,289
Heat into Building Mass/Product (BTUs)	5,172,333	3,351,291

**Figure 46: Heat transfer to air versus product and building mass for both simulations**

For both of the subject test spaces, Figure 46 shows that the heat required to raise the temperature of the air by the observed temperature rise during demand response is only about 2% of the total calculated heat flux into the space from the calibrated energy models. The remaining heat is assumed to be absorbed by the building mass and the space contents, including racking, packaging, and product.

For test space #2, the building operator roughly estimated the total product held in the space at the time of the demand response simulation to be approximately 3 million pounds of frozen shrimp. If 100% of the calculated heat absorbed by the building mass and product is assumed to be absorbed by just the product, and using the known thermodynamic properties of frozen shrimp and the rough estimate of total product mass held within the space, the bulk average temperature rise of the product can be estimated as approximately 2.2°F, as shown in Figure 47.



**Figure 47: Air and product temperature rise at peak of demand response event**

The actual product temperature rise would be less than the calculated value, because some of the heat is absorbed by the other contents of the space, such as racking and packaging. Also, the calculated temperature rise is the bulk average—in reality, the product near the exposed sides of the packaging mass will be warmer than the center-of-mass product temperature.

## C.5 Summary and Conclusions

Refrigeration systems may require 24 hours or more to completely recover from a demand response event. If a system participates in demand response on two or more consecutive days, the temperature rise of each consecutive demand response event may be greater than the previous day. If a facility utilizes a permanent load-shift control strategy, the system daily peak load and daily peak space temperature rise will re-balance and a higher steady-state value.

The maximum space temperature during demand response or load-shift events is significantly curtailed by precooling (e.g. over-cooling the product before a demand response event), but the magnitude of the range in space temperature is generally not affected. The duration of the recovery period after a demand response event is inversely proportional to the time spent precooling before the event, but the average fan speed (and the consumed power) is higher with the precooling strategy, because fans are at full-speed during precooling hours.

Building mass and stored product temperature greatly influences the total space temperature rise during a demand response event, because the building and product mass absorb the majority of the heat flux into the space during demand response.